DOCTORAL THESIS

Neuromuscular, Biochemical, Endocrine and Physiological Responses of Elite Rugby League Players to Competitive Match-Play

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NEUROMUSCULAR, BIOCHEMICAL, ENDOCRINE AND PHYSIOLOGICAL RESPONSES OF ELITE RUGBY LEAGUE PLAYERS TO COMPETITIVE MATCH-PLAY.

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DECLARATION

This work has not previously been submitted for a degree or diploma in any University. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

Signed: _____

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PREFACE

In 2009, the National Rugby League (NRL) was the most watched sport on Australian television (TV) (403). A review of TV ratings at the completion of the 2009 NRL season revealed that 60 of the top 100 rating subscription TV programs were NRL matches (403), exceeding TV ratings of all other football codes in Australia. In particular, NRL matches out-rated Australian Football League (AFL) matches on both free to air and subscription TV (403). The NRL is experiencing unprecedented popularity with improved TV ratings for Friday night and Sunday afternoon matches and an average crowd attendance of 16,051, an increase of 2.93 % on 2008 figures. In 2009, the Telstra premiership recorded the highest regular season attendance in the history of Rugby League with 3,081,839 people attending the 26 rounds of regular season matches. NRL matches on subscription TV reached more than 3.6 million viewers in 2009, while on average, each regular season round in the NRL reached more than 2.7 million viewers with more than 220,000 listeners tuning into Rugby League on radio every weekend throughout the season (403).

To assist the NRL to remain the centre piece in the fee to air and subscription TV schedule, there is a considerable need for a substantial and ongoing commitment to excellence by coaches, sports scientists and strength and conditioning practitioners to advance the knowledge base regarding match preparation, match-play performance and best practice methodologies during the post-match recovery period. Despite the professional status of the NRL as an international sport with a global viewing audience, there remains a lack of research in the key areas of player response to the demands of match-play and the pattern of neuromuscular, endocrine and biochemical recovery in elite Rugby League in comparison to other football codes such as AFL, Rugby Union and Soccer. With the exception of Dr Dan Baker from the Brisbane Broncos, who has set the bench mark for applied strength and power research in professional Rugby League for over 10 years, the majority of research has consisted of retrospective reporting of player anthropometric data, injury rates and comparisons of junior, amateur, and semi-professional player performance characteristics.

The motivation for the present body of work arose from a conversation with Olympic weightlifting coach, Mr Lyn Jones at a Sports Power Coaching accreditation course attended by the author in Brisbane in 2005. During the course of one of many conversations regarding athlete recovery and preparation, Lyn pondered the age-old question of how can a coach determine when an athlete has recovered sufficiently from a workout or competitive performance to enable that athlete to return to training in preparation for subsequent performance? The lack of information pertaining to the physiological demands of Rugby League match-play under current defensive rules, interchange

limitations and the introduction of two on-field referees is evident in any systematic review of the literature. Furthermore a review of the literature revealed no study had examined the neuromuscular, endocrine or biochemical response of elite Rugby League players to competitive match-play. No study has investigated the time course associated with a return to pre-match neuromuscular, endocrine or biochemical measures during the post-match recovery period following NRL match-play.

The present body of work was therefore undertaken to establish the neuromuscular, endocrine, biochemical and physiological physiological demands of match-play in the NRL and to determine the anabolic:catabolic endocrine behaviour, neuromuscular fatigue and muscle damage immediately post-match and for a period of up to 5 days post-match. By determining the time course associated with a return to pre-match hormonal homeostasis and neuromuscular function, the effectiveness of recovery strategies could be established. An increased knowledge base in relation to the neuromuscular, endocrine, biochemical and physiological pattern of response following elite Rugby League match-play may enable a more accurate identification of when players could return to training without interfering with the short term post-match recovery period to be recognised, and preparation for subsequent performance optimised.

NAVIGATION OF THE THESIS

This thesis "by publication" comprises five experimental studies presented as five individual chapters. Each of the five experimental studies are "In press". All papers are presented in the format accepted for publication and include an introduction, review of the literature, methods, results and discussion sections. Each experiment builds on the previous experiment to increase the knowledge of short-term and long-term post-match physiological, neuromuscular, endocrine, and biochemical responses of elite players as they relate to elite Rugby League match-play.

There are eight Chapters which make up the present thesis. Chapter 1 provides an introduction of the purpose and significance of the research, presents hypothesis associated with each study and outlines the research questions. Chapter 2 provides an overview of the literature with specific reference to the physiological demands and movement patterns associated with Rugby League match-play. The reader is introduced to Global Positioning System (GPS) technology for performance analysis in sports and the validity and reliability of portable GPS units is considered. Chapter 2 also contains a review of neuromuscular fatigue and sports performance with a particular focus on the assessment of movements incorporating the stretch shortening cycle (SSC) to determine neuromuscular fatigue and the role of muscle force, power and the rate of force development in team sports. A review of the literature pertaining to endocrine indices of fatigue, muscle damage and recovery following contact sport concludes Chapter 2.

Chapter 3 is Experimental Study 1, and has been accepted for publication as:
McLellan, C.P., Lovell, D.I., & Gass, G.C. The Role of Rate of Force Development on Vertical Jump Performance. Journal of Strength and Conditioning Research, (In Press, 2010).

Chapter 4 is Experimental Study 2, and has been accepted for publication as:
McLellan, C.P., Lovell, D.I., & Gass, G.C. Performance Analysis of Elite Rugby League Match-Play using Global Positioning Systems. Journal of Strength and Conditioning Research, (In Press, 2010).

Chapter 5 is Experimental Study 3, and is presented in the format accepted for publication:
McLellan, C.P., Lovell, D.I., & Gass, G.C. Creatine Kinase and Endocrine Responses of Elite Players Pre, During and Post Rugby League Match-Play. Journal of Strength and Conditioning Research, 24(11): 2908-2919, 2010.

Chapter 6 is Experimental Study 4, and has been accepted for publication as:
McLellan, C.P., Lovell, D.I., & Gass, G.C. Markers of Post-Match Fatigue in Professional Rugby League Players. Journal of Strength and Conditioning Research, (In Press, 2010).

Chapter 7 is Experimental Study 5, and has been accepted for publication as:
McLellan, C.P., Lovell, D.I., & Gass, G.C. Biochemical and Endocrine Responses to Impact and Collision During Elite Rugby League Match-Play. Journal of Strength and Conditioning Research, (In Press, 2010).

The Journal of Strength and Conditioning Research was specifically selected as the refereed Journal to receive the results of Experiments 1 – 5. It was reasoned that if clinical practice was to improve then the results of Experiments 1 – 5 should be presented in sources that were widely read by Strength and Conditioning and Sports Science practitioners. There was a clear intent that research should inform practice and the Journal of Strength and Conditioning Research was therefore the journal of choice.

In addition to the "In press" papers listed in Chapters 3, 4, 5, 6, and 7, the research conducted in completion of the present thesis also contributed to the preparation of the following poster presentations:

McLellan, C.P., Lovell, D.I., & Gass, G.C. Muscle enzyme and endocrine responses of elite players to Rugby League match-play. Journal of Science and Medicine in Sport, 12(6) Dec Sup; 106-107, 2009. Presented at the Australian Conference of Science and Medicine in Sport, 14 – 17 October 2009, Brisbane.

Chapter 8 presents the overall discussion and conclusions that summarise the findings of the experimental studies and outlines recommendations for future research to increase our understanding of elite Rugby League match-play.

ACKNOWLEDGEMENTS

I would like to acknowledge a number of people for their support and encouragement throughout the period of my doctoral candidature. Throughout my entire professional career I have received unwavering support from my wife Vanessa and my very understanding children, Ronan and Remi. My family have sacrificed much to allow me to pursue my career and for that words cannot express my gratitude.

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I would also like to acknowledge and thank the Gold Coast Titans NRL Team administration, coaching staff and players, all of whom have been remarkably accommodating during the completion of all research projects that have culminated in the development of the thesis. Sincere thanks also to my friend and tireless assistant at the Gold Coast Titans, Mr Dan Ferris, for his assistance throughout the course of this research.

ABSTRACT

The primary aim of this thesis was to advance our knowledge of the neuromuscular, endocrine, biochemical and physiological responses of elite Rugby League players during competitive match-play. The secondary aim of this thesis was to examine the effects of the short term recovery phase post-match and the associated time-course for a return to hormonal homeostasis, neuromuscular function and musculoskeletal recovery following match-play.

Chapter 3 (Experimental Study 1 – Paper 1)

The purpose of this study was to examine i) the relationship between rate of force development (RFD) and vertical jump (VJ) performance during a counter movement jump ii) the reliability of RFD recorded during the counter movement jump (CMJ) and squat jump (SJ) forms of the VJ. Twenty three physically active men aged 23 ± 3.9 yr participated in the study. Subjects completed three unloaded CMJ and three unloaded SJ in random order on a force plate. RFD was measured during CMJ and SJ movements with vertical jump displacement (VJD) measured simultaneously during the CMJ only. Subjects incorporated arm swing to their CMJ technique to reach up as high as possible and VJD was measured. All SJ were executed with both hands on the hips throughout the full range of movement. Peak rate of force development (PRFD), peak force (PF) and time to peak force (TPF) were significantly correlated to VJD during the CMJ (r = 0.68, r = 0.51 and r = -0.48 respectively). The RFD and TPF during the CMJ and SJ were associated with low test re-test reliability (coefficient of variation [CV]: 11.8 – 17.9 %). Peak and average power, PF and VJD produced high test retest reliability (CV: 2.8 – 5.1 %) during both the CMJ and SJ movements. However, caution must be used when interpreting data using PRFD due to low re-test reliability. The results indicate that PRFD, a measure of explosive strength, and PF, a measure of maximal strength are the primary contributors to VJD during the CMJ. Measurement of selected force-time variables during the CMJ and SJ demonstrate acceptable levels of reliability for inclusion in functional assessment protocols to determine the influence of acute or chronic exercise on SSC performance in physically active men.

Chapter 4 (Experimental Study 2 – Paper 2)

The aim of the present study was i) to examine the physiological demands of competitive Rugby League match-play using portable Global Positioning Systems (GPS) to monitor player's movement

patterns and heart rate (HR) and ii) examine positional comparisons to determine if a player's physiological requirements are influenced by their playing position during Rugby League match-play. Twenty two elite male Rugby League players were monitored during five regular season competition matches using portable GPS software. There was no significant difference in the total distance travelled between backs (5573 ± 1128 m) and forwards (4982 ± 1185 m) during match-play. Backs and forwards had an average HR of approximately 80 % of their maximum HR (162 ± 11 and 165 ± 12 $b \cdot min^{-1}$ respectively) throughout each match. Backs achieved greater maximum running speed (8.6 ± 0.7 $m \cdot sec^{-1}$), completed a greater number of sprints (18 ± 6), had less time between sprints (3.2 ± 1.1 min), achieved a greater total duration of sprinting (44.7 ± 9.1 s) and covered more distance sprinting (321 ± 74 m) than forwards (6.8 ± 0.7 $m \cdot sec^{-1}$, 11 ± 5, 5.2 ± 2.2 min, 25.8 ± 9.2 s and 153 ± 38 m respectively). The present study provides insight into the high intensity nature of elite Rugby League competition incorporating real-time accelerometer and GPS technology to establish key performance indicators of match-play. The results identify significant positional differences in total distances covered, running speed profiles and the physiological demands of match-play. Position specific demands on aerobic and anaerobic energy systems during elite Rugby League match-play should be considered when planning post-match recovery protocols and training activities to optimise subsequent performance.

Chapter 5 (Experimental Study 3 – Paper 3)

The purpose of the present study was to i) examine player movement patterns to determine total distance covered during competitve Rugby League match-play using GPS and ii) examine pre, during and post-match plasma creatine kinase (CK) and endocrine responses to competitive Rugby League match-play. Seventeen elite Rugby League players were monitored for a single game. Player movement patterns were recorded using portable GPS units (SPI-Pro, GPSports, Canberra, Australia). Saliva and blood samples were collected 24 hr pre-match, 30 min pre-match, 30 min post-match and then at 24 hr intervals for a period of 5 days post-match to determine plasma CK and salivary testosterone (sTest), cortisol (sCort) and testosterone:cortisol ratio (sT:C). The change in the dependent variables at each sample collection time was compared to 24 hr pre-match measures. Backs and forwards travelled distances 5747 ± 1095 m and 4774 ± 1186 m respectively throughout the match. The sCort and plasma CK increased significantly ($p < 0.05$) from 30 min pre-match to 30 min post-match. Plasma CK increased significantly ($p < 0.05$) post-match, with peak plasma CK concentration measured 24 hr post-match (889.25 ± 238.27 $U.L^{-1}$). Cortisol displayed a clear pattern of response with significant ($p < 0.05$) elevations up to 24 hr post-match, compared with 24 hr pre-

match. The GPS was able to successfully provide data on player movement patterns during competitive Rugby League match-play. The plasma CK and endocrine profile identified acute muscle damage and a catabolic state associated with Rugby League match-play. A return to normal testosterone:cortisol ratio within 48 hr post-match indicates that a minimum period of 2 days is required for endocrine homeostasis post-competition. Plasma CK remained elevated despite 120 hr of recovery post-match identifying that a prolonged period of at least 5 days of modified activity is required to achieve full recovery following muscle damage during competitive Rugby League match-play. The results support the inclusion of plasma CK and salivary endocrine measures as objective markers of muscle damage and stress experienced by elite Rugby League players pre, during and post-match. Furthermore, the results indicate that plasma CK, sCort, sTest and sT:C ratio are meaningful measures to monitor individual player tolerance to training and competitive loads and should be considered when developing recovery and training plans over the course of an extended season of weekly elite Rugby League competition.

Chapter 6 (Experimental Study 4 – Paper 4)

The aim of the present study was to identify neuromuscular, biochemical and endocrine markers of fatigue following Rugby League match-play. Seventeen elite Rugby League players were monitored for a single match. Peak rate of force development (PRFD), peak power (PP) and peak force (PF) were measured during a countermovement jump (CMJ) on a force plate pre and post match-play. Saliva and blood samples were collected 24 hr pre-match, 30 min pre-match, 30 min post-match and then at 24 hr intervals for a period of 120 hr to determine plasma creatine kinase concentration ([CK]) and salivary cortisol concentration ([sCort]). There were significant ($p < 0.05$) decreases in PRFD and PP up to 24 hr post-match with PF significantly ($p < 0.05$) decreased immediately post-match. The [sCort] significantly ($p < 0.05$) increased from 24 hr pre-match to 30 min pre-match and up to 24 hr post-match compared to 24 hr pre-match. Plasma [CK] significantly ($p < 0.05$) increased 30 min post-match with a peak occurring 24 hr post-match and remained elevated above 24 hr pre-match for at least 120 hr post-match. There were significant ($p < 0.05$) correlations between the increase in plasma [CK] and reduction in PRFD 30 min post-match and 24 hr post-match. The [sCort] was significantly ($p < 0.05$) correlated with the reduction in PF 30 min post-match. Results demonstrate that neuromuscular function is compromised and results in significant impairment of PRFD, PF and PP for up to 48 hr following elite Rugby League match-play. Elevated plasma [CK] despite 120 hr recovery indicates that damage to muscle tissue following Rugby League match-play may persist for at least five days post-match. Despite the prolonged presence of elevated plasma [CK] post-match, strength

training 48 hr post-match may have resulted in a compensatory increase in PRFD supporting the inclusion of strength training during the short-term post-match recovery period. The CMJ offers a functional analysis measure of neuromuscular fatigue and exercise induced muscle damage and should be considered to establish a comprehensive profile of individual adaptation and recovery following elite Rugby League match-play.

Chapter 7 (Experimental Study 5 – Paper 5)

The purpose of the present study was to investigate the relationship between the pre-match and short term post-match biochemical and endocrine responses to the intensity, number and distribution of impact forces associated with collisions during elite Rugby League match-play. Seventeen elite male Rugby League players each provided blood and saliva samples 24 hr pre-match, 30 min pre-match, 30 min post-match and then at 24 hr intervals for a period of 5 days post-match to determine plasma creatine kinase concentration ([CK]) and salivary cortisol concentration ([sCort]). The intensity, number and distribution of impact forces experienced by players during match-play were recorded using portable Global Positioning Systems (GPS) and integrated accelerometer. The change in the dependent variables at each sample collection time was compared to 24 hr pre-match and 30 min pre-match measures. Plasma [CK] and [sCort] increased significantly *(*$p < 0.05$) during match-play. Significant correlations ($p < 0.05$) were observed between the number of hit-ups and peak plasma [CK] 24 hr post match, 48 hr post-match and 72 hr post-match ($p < 0.05$). The number of impacts recorded in Zone 5 (8.1 – 10.0 G) and Zone 6 (> 10.1 G) during match-play were significantly correlated ($p < 0.05$) to plasma [CK] 30 min post-match, 24 hr post, 48 hr post and 72 hr post-match. The GPS and integrated accelerometer was able to provide data on the intensity, number and distribution of impacts resulting from collisions during match-play. Elite Rugby League match-play resulted in significant skeletal muscle damage, and was highly dependent on the number of heavy collisions > 8.1G. Plasma [CK] remained elevated 120 hr post-match identifying that at least five days of modified activity is required to achieve full recovery following elite Rugby League match-play. A gradual reduction in plasma [CK] during the five day post-match recovery phase coincided with reduced training loads and no additional physical trauma indicting plasma [CK] can be used to monitor acute recovery from elite Rugby League match-play.

LIST OF PUBLICATIONS

1. **McLellan, C.P.,** Lovell, D.I., & Gass, G.C. The Role of Rate of Force Development on Vertical Jump Performance. Journal of Strength and Conditioning Research, In Press, 2010.

2. **McLellan, C.P.,** Lovell, D.I., & Gass, G.C. Performance Analysis of Elite Rugby League Match-Play using Global Positioning Systems. Journal of Strength and Conditioning Research, In Press, 2010.

3. **McLellan, C.P..** Lovell, D.I., & Gass, G.C. Creatine Kinase and Endocrine Responses of Elite Players Pre, During and Post Rugby League Match-Play. Journal of Strength and Conditioning Research, 24(11): 2908-2919, 2010.

4. **McLellan, C.P.,** Lovell, D.I., & Gass, G.C. Markers of Post-Match Fatigue in Professional Rugby League Players. Journal of Strength and Conditioning Research, In Press, 2010.

5. **McLellan, C.P.,** Lovell, D.I., & Gass, G.C. Biochemical and Endocrine Responses to Impact and Collision During Elite Rugby League Match-Play. Journal of Strength and Conditioning Research, In Press, 2010.

LIST OF CONFERENCE PROCEEDINGS

1. **McLellan, C.P.,** Lovell, D.I., & Gass, G.C. Muscle enzyme and endocrine responses of elite players to Rugby League match-play. Journal of Science and Medicine in Sport, 12(6) Dec Sup; 106-107, 2009. Presented at the Australian Conference of Science and Medicine in Sport, 14 – 17 October 2009, Brisbane.

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LIST OF SYMBOLS AND ABBREVIATIONS

Dot	[·]	above any symbol indicates a time derivative
Dash	[-]	above any symbol indicates a mean value

SYMBOLS

α	alpha
β	beta
r	Pearsons product moment correlation coefficient
p	statistical significance
µ	micro
°C	temperature in degrees celsius
±	plus or minus
%	percent
>	greater than
<	less than

UNITS OF MEASUREMENT

ANOVA	analysis of variance
$b \cdot min^{-1}$	beats per minute
cm	centimetres
CV	coefficient of variation
ES	effect size
ft	feet
g	grams
G	gravitational force
hr	hours
$hr \cdot wk^{-1}$	hours per week
HR	heart rate
HR_{max}	maximum heart rate
Hz	Hertz
HSD	Tukey's honestly significant difference

ICC	intraclass correlation coefficient
kg	kilogram
km·hr $^{-1}$	kilometres per hour
km·wk $^{-1}$	kilometres per week
m	metres
min	minutes
m·min^{-1}	metres per minute
mm	millimetre
ms	millisecond
m.sec^{-1}	metres per second
ms²	metres per second squared
N	Newton
ng·mL^{-1}	nanogram per millilitre
nm·L^{-1}	nanomole per litre
N·s $^{-1}$	Newton per second
pg·mL^{-1}	picograms per millilitre
rpm	revolutions per minute
s	seconds
SD	standard deviation
SEE	standard error of estimate
SEM	standard error of mean
TE	typical error
VO_2 max	maximum oxygen uptake
U·L^{-1}	units per litre
W	Watts
wk	week
yr	years
µg.dL^{-1}	micro-gram per decilitre
µL	micro litre

ENZYMES / METABOLITES

ACTH	adrenocorticotrophic hormone
ADP	adenosine diphosphate
ATP	adenosine triphosphate
Ca^{2+}	calcium
CGB	cortsiol binding globulin
CK	creatine kinase
[CK]	creatine kinase concentration
CK-BB	brain creatine kinase isoform
CK-MB	cardiac muscle creatine kinase isoform
CK-MM	skeletal muscle creatine kinase isoform
[Cort]	cortisol concentration
FSH	follicle stimulating hormone
GOT	glutamic oxaloacetic transaminase
H^+	hydrogen ion
K^+	potassium
LDH	lactate dehydrogenase
LH	leutenising hormone
Na^+	sodium
NH^3	ammonia
PCr	phosphocreatine
Pi	inorganic phosphate
sCort	salivary cortisol
[sCort]	salivary cortisol concentration
SHBG	sex hormone binding globulin
sT:C	salivary testosterone:cortisol ratio
sTest	salivary testosterone
[sTest]	salivary testosterone concentration
T:C	testosterone:cortisol ratio

VARIABLES AND ABBREVIATED TERMS

1RM	one repetition maximum
AFL	Australian Football League
ARFD	average rate of force development
AF	average force
AP	average power
BT	bench throw
BUHREC	Bond University Human Research Ethics Committee
CHO	carbohydrate
CMJ	countermovement jump
CNS	central nervous system
CWI	cold water immersion
DJ	drop jump
DOMS	delayed onset muscle soreness
DWR	deep water running
EE	elbow extensors / elbow extension
EF	elbow flexors / elbow flexion
e.g.	example
EIMD	exercise induced muscle damage
EMG	electromyography
EMS	electromyostimulation
ES	electrical stimulation
F	force
FTV	force-time variable
GCT	ground contact time
GPS	global positioning system
GRF	ground reaction force
HFF	high frequency fatigue
HPA	hypothalamic-pituitary axis
H-reflex	hoffman reflex
KE	knee extension / knee extensor
KF	knee flexion / knee flexor
KPI's	key performance indicators
LIST	Loughborough Intermittent Shuttle Test
LFF	low frequency fatigue
MARP	Maximal anaerobic running power

MHC	myosin heavy chain
MIVC	maximum isometric contraction
MMG	mechanomyography
MN	motor neuron
MPF	mean power frequency
MRFD	maximum rate of force development
M-wave	skeletal muscle action potential
MU	motor unit
MVC	maximum voluntary contraction
n	number of subjects
NCAA	National Collegiate Athletic Association (USA)
NM	neuromuscular
NPC	National Provincial Championship (New Zealand Rugby Union)
NRL	National Rugby League
NSWPL	New South Wales Premier League
P	power
PF	peak force
PP	peak power
RFD	rate of force development
PRFD	peak rate of force development
RBE	repeated bout effect
Reps	repetitions
RIA	radioimmunoassay
RM	repetition maximum
ROM	range of movement
RSA	repeated sprint ability
RSAT	repeated sprint ability test
RT	resistance training
SA	selective availability
SJ	squat jump
SR	sarcoplasmic recticulum
SSC	stretch shortening cycle
SPSS	statistical package for the social sciences
T1	first thoracic vertebrae
TMA	time motion analysis
TMS	transcranial magnetic stimulation

TPF	time to peak force
T-tubule	transverse tubule
TV	television
US	United States
USA	United States of America
USG	urine specific gravity
UV	ultraviolet
VA	voluntary activation
VJ	vertical jump
VJD	vertical jump displacement
VL	vastus lateralis
VM	vastus medialis
WiFi	wireless fidelity

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CHAPTER 1

1.1 Introduction

Rugby League is a high intensity collision sport played by two teams of seventeen players, with each match played over two 40 minute (min) periods separated by a ten min half time rest interval. At any one time there are thirteen players from each team on the playing field and four interchange players situated on the sideline interchange bench. Recently, the player replacement interchange rule in the NRL has undergone substantial review. Player replacement and interchange rules in the NRL have evolved from a maximum of four replacements per match prior to 1995 to unlimited interchanges during seasons 1995 to 1997. At the commencement of the 1998 season interchange rules were reduced to twelve interchanges per match until 2007 when the number of interchanges was further reduced to the current limit of ten per match. Fewer player interchange opportunities during NRL match-play has lead to a general trend of position specific interchanges during the course of competition, primarily involving front row and back row positional players. An additional outcome of changes in interchange rule structures is the establishment of specialised 'interchange players' that participate in short periods of on-field match-play to provide starting players with pre-determined rest periods of ten to fifteen min to maintain the intensity of match-play, optimise individual player contribution on-field and facilitate team performance.

The general pattern of player interchange activity during 80 min of match-play in the NRL is as follows:

- 20 - 25 min interchange x 2 forwards (interchange 1 and 2)
- 25 - 30 min interchange x 2 forwards (interchange 3 and 4)
- 55 – 60 min interchange x 2 forwards (interchange 5 and 6)
- 60 – 65 min interchange x 2 forwards (interchange 7 and 8)
- Interchange 9 and 10 commonly managed by coaching staff to address player replacement requirements associated with on-field injury during match-play.

The on-field participation role of the specialised interchange player in the NRL may vary from one to three bouts of ten to fifteen min bouts of match-play for a total of 20 – 50 min played. Starting front row and back row positional players may be provided with one to two rest periods of ten to fifteen min duration throughout the course of match-play resulting in a total number of minutes played of 50 – 70 min. Accordingly, the physiological demands of match-play for interchange players has lead to an

increased emphasis on the development of anaerobic energy systems to assist players undertake high intensity intermittent exercise for durations of ten to fifteen min. The overall influence of regular interchange of fatigued players with new or recently rested players is maintenance of high intensity team match-play and a concomitant requirement for all players to repeatedly undertake high intensity intermittent bouts of aerobic and anaerobic exercise for the full duration of each 40 min half of a match.

The influence of the introduction of two on-field referees in the NRL at the commencement of the 2010 regular season is speculative. A comparison of unpublished match-play GPS data recorded by the author regarding total distance travelled, exercise to rest ratios, tackles performed and position specific sprint profile over the course of the 2009 and 2010 NRL regular season periods indicates no remarkable change in the physiological requirements of match-play officiated by a single on-field referee in 2009 and two on-field referees in 2010.

During offensive play, each team is permitted six tackles to advance the ball down the field into the opposition's territory and score a try (aka touch down) (159, 169, 181, 182, 225). Passing and running are the two primary means of advancing the ball, however the ball may be kicked at any time into the oppositions' territory to gain field position or other strategic and / or try scoring opportunities (225, 340). An offside rule applies. At the completion of each set of six tackles if the offensive team has not scored a try and is in possession of the ball, the ball is relinquished to the opposition to commence its set of six tackles (159). Each player on field therefore has offensive and defensive match-play responsibilities.

Although specific on field positions exist, there is no limitation as to where players can move during match-play. Typically, players are broadly characterised as forwards (i.e., all players involved in the scrum, six per team) or backs (i.e., all players not involved in the scrum, seven per team) (309). Team positions may also be classified according to specific playing position (i.e., front row forward, hooker, second row forward, lock forward, scrum half, five-eighth, centre three quarter, winger and fullback) or according to positional subgroups on the basis of common performance and / or field position characteristics (i.e., front rowers, back-rowers, inside backs / halves and outside backs) (159, 169, 309, 340). The physiological, anthropometric and injury characteristics of junior (21, 98, 161, 167) , amateur (160, 166), semi-professional (92, 93, 164, 165) and professional (20, 24, 159, 181, 225, 309) Rugby League players have been reported previously. Time-motion analysis (TMA) studies have added to our understanding of the rigors of match-play at the semi-professional and professional levels (246, 307, 308, 396, 397), however no studies have investigated the movement characteristics of elite players using Global Positioning Systems (GPS) to quantify the variables of total distance covered, sprint profile and heart rate (HR) response under current rule structures.

The NRL is comprised of 16 teams that play in a National competition consisting of 26 rounds with each club scheduled two bye rounds between rounds 10 and 20 of the regular season period. Following the 26 week regular season period, the top eight teams participate in a four week finals series (McIntyre System) to determine the premiership winning team each season. Teams that compete in the NRL are based in the major metropolitan areas of Queensland (Gold Coast Titans, Brisbane Broncos and North Queensland Cowboys (Townsville)), the Australian Capital Territory (Canberra Raiders), Victoria (Melbourne Storm), New South Wales (Cronulla Sharks, Eastern Suburbs Roosters, Manly Sea Eagles, Newcastle Knights, Parramatta Eels, Penrith Panthers, South Sydney Rabbitohs, Sydney Bulldogs, St George-Illawara Dragons, Wests Tigers) and New Zealand Warriors (Auckland).

Anecdotally, a common feature of team performance during the course of the NRL season is a mid-season slump in performance that may be associated with overwork and / or under-recovery of players due to training and match-play demands that may include representative commitments. The extended exposure of players to the demands of training and match-play may lead to altered neuromuscular and endocrine function and may contribute to the development of under-recovery, overreaching or overtraining syndrome in team sport athletes (90, 95-97). Analysis of pre and post-match measures of neuromuscular performance, biochemical markers of skeletal muscle damage and the anabolic:catabolic endocrine status would therefore constitute meaningful monitoring methodologies for elite Rugby League players.

The use of endocrine and biochemical measures to monitor player responses to competition and recovery are commonplace in elite sports (86, 110, 137, 216, 218, 259). However, no studies have considered the impact of elite Rugby League match-play on measures of testosterone, cortisol or the ratio of testosterone to cortisol to examine the relative anabolic or catabolic state of an individual. The use of endocrine measures to provide a potential marker of elite Rugby League players' response to training or competition or to reflect recovery status of players is unreported. The role of endocrine measures as markers of player status and recovery remains speculative in elite Rugby League therefore further investigation of these hormones is warranted. The present thesis will attempt to resolve questions regarding the endocrine response of elite Rugby League players to match-play and the time course associated with a return to endocrine homeostasis following match-play.

The NRL season comprises a 24 match schedule conducted over a 26 week period from March to September. In preparation for the up-coming season, teams will complete several months of training and then participate in several trial matches in the month prior to the first match of the NRL season. Players therefore may participate in up to 46 weeks of high volume and high intensity training throughout the off-season, pre-season and in-season periods each year. These high training loads may

increase the risk of player overuse injury, burn-out and under-performance that may be associated with overreaching or overtraining (202) in elite Rugby League players (97). Due to the prolonged training and competition periods experienced by players in the NRL, the assessment of acute and cumulative fatigue and implementation of effective recovery monitoring protocols are key considerations for the coaching and strength and conditioning staff. Throughout the course of the extended NRL season, match-scheduling, travel, and limited training opportunities influence on field performance. Accordingly, key performance indicators (KPI's) associated with elite Rugby League match-play include the ability to identify and monitor neuromuscular fatigue, implement fatigue prevention strategies and optimise the post-match recovery period to prepare for subsequent match-play.

In addition to the influence of elite Rugby League match-play on player endocrine status, KPI's in the form of functional measures of strength, speed, power activities may also serve as appropriate markers of neuromuscular fatigue and recovery in athletes (94-97, 463). The incorporation of neuromuscular and endocrine assessment methods may be useful to monitor elite Rugby League players following match-play and optimise their recovery to facilitate subsequent performance. Historically, studies that have examined neuromuscular fatigue have been limited by data collection methods that require laboratory based testing equipment and time consuming testing procedures that impede the simultaneous measurement of multiple subjects or large groups of subjects (50, 88). The development of portable force plates and other portable measurement devices such contact mats, position transducers, V-scopes, accelerometers, rotary encoders and yardsticks (70, 107, 207, 292, 295, 418) have enabled coaches, sports scientists and strength and conditioning coaches to assess players' at more regular intervals and at locations outside the laboratory.

To overcome the limitations associated with functional assessment protocols, the inclusion of easy to administer functional evaluation methods such as the countermovement jump (CMJ) and squat jump (SJ) have become commonplace in professional sports to monitor athlete adaptation to the demands of training and competition. The performance of tasks such as the CMJ and SJ may be influenced by neuromuscular, biochemical and metabolic factors, such as metabolite accumulation, depletion of energy substrates and elevated plasma intracellular enzymes (53, 54, 288, 323, 355, 365), thereby adding to the complexity of functional task assessment to determine lower limb force-time-power characteristics and neuromuscular fatigue following competition. The specific vertical jump (VJ) testing protocols implemented to assess neuromuscular performance in athletes (e.g. single or multiple VJ), the timing of data collection following performance and the specific characteristics of CMJ and SJ may also contribute to variation in the determination of neuromuscular fatigue. Recently, several studies (94-97) have supported the inclusion of VJ analysis to monitor neuromuscular fatigue and recovery in Rugby League players. The effects of high intensity, intermittent exercise during team sport performance and repeated blunt force trauma, such as that experienced by elite Rugby League

players during match-play is largely unknown. Accordingly, there are limited data (86, 87, 160, 216) that consider functional task assessment to determine neuromuscular fatigue following elite contact sport performance. Systematic analysis of neuromuscular fatigue in response to elite Rugby League match-play may provide insight to early detection of compromised neuromuscular status and subsequent decrements in match-play performance.

1.2 Purpose of the Research

Despite the existence of professional Rugby League competitions in the southern and northern hemispheres, no studies have examined the neuromuscular, endocrine and biochemical responses of elite players to match-play in the NRL. Consequently, the expected pattern of neuromuscular fatigue and endocrine responses to elite contact sports performance and training loads is speculative, and the influence of the demands of weekly elite Rugby League match-play is unknown.

The CMJ and SJ are common methods utilised by researchers and practitioners to assess athlete performance and neuromuscular fatigue during intermittent high intensity stretch-shortening cycle (SSC) exercise such ast that performed during Rugby League match-play. No studies however have considered the relative contribution of PF, PP and PRFD measures on CMJ and SJ performance in elite Rugby League players to monitor the acute response to match-play and the manifestation of neuromuscular fatigue. The purpose of the present research therefore was to examine the relationship between PF, PP, PRFD and VJ performance utilising a portable force-plate to determine the reliability, relative contribution and most appropriate measures to monitor neuromuscular fatigue during the CMJ and SJ in elite Rugby League players (experimental study one).

Relatively few data exist regarding the performance characteristics and physiological demands of elite Rugby League match-play and no studies have investigated the demands of NRL match-play using GPS and integrated accelerometer technology. The second purpose of the present research therefore was to examine the physiological demands of NRL match-play using portable GPS, integrated accelerometer and HR monitor technology to determine player movement patterns and HR to identify the position specific requirements of elite Rugby League match-play (experimental study two). The establishment of position specific performance characteristics associated with elite Rugby League match-play in the NRL under current defensive and interchange rules provided the basis upon which subsequent experimental studies that constitue the present research were developed.

Building upon the findings of experimental studies one and two, the third purpose of the present research was to examine player movement patterns during competitive Rugby League match-play using GPS and integrated accelerometer technology and determine the corresponding pre, during and post-match plasma CK, sCort, sTest and sT:C ratio to examine the manner of their response and assess the magnitude of change in these biochemical and endocrine measures in response to elite Rugby League match-play (experimental study three). No studies have examined the post-match fatigue in elite Rugby League players. To increase our understanding the demands of elite Rugby League match-play, an additional purpose of the present research was to complement the findings of previous experimental studies to examine neuromuscular fatigue via CMJ and SJ analysis pre, and post- elite Rugby League match-play (experimental study four). The investigation of the neuromuscular, biochemical and endocrine measures in response to Rugby League match-play substantiates the primary theme of the present thesis and establishes a new standard for applied sports science analysis of elite NRL match-play. Finally, the consequences of blunt force trauma resulting from contact between players during Rugby League match-play were examined via the analysis of biochemical and endocrine responses to the intensity, number and distribution of impacts associated with collisions measured via portable accelerometry during elite Rugby League match-play (experimental study five).

1.3 Significance of the Research

The present research systematically examined the time-course of neurosmuscular, biochemical, endocrine and physiological responses of players pre, during and following elite Rugby League match-play. Despite the existence of an elite NRL competition and the professional status of players participating in that competition, there remains a paucity of research regarding the requirements of actual match-play and subsequent recovery periods in preparation for subsequent performance. To date, the propensity of research in the sport of Rugby League has consisted of retrospective analyses of the applied physiology, anthropometric characteristics, physical attributes of players and injury rates of semi-professional, amateur or youth populations. Such retrospective analyses are not highly relevant or indicative of elite level players or elite competition. Studies that have examined the time-motion and demands of competition have incorporated traditional notational player tracking methodologies under outdated rule structures and pre-existing interchange restrictions, limiting the application of such data to the current match-play requirements. The present research provides a novel analysis of NRL match-play using contemporary player tracking methodologies in the form of portable GPS analysis and the simultaneous collection of physiological data reflecting the adaptation of players to match-specific performance requirements. While the use of GPS analysis of match-play is now

commonplace in the NRL, no studies have reported the characteristics of performance under current rule structures. Hence the present research adds to our understanding of the requirements of elite Rugby League match-play and lends support to the use of GPS to monitor elite Rugby League players during competition.

In the past decade there has been a considerable emphasis on improving recovery practices following elite Rugby League match-play. No studies however have examined the neuromuscular, biochemical or endocrine responses of elite players following NRL match-play. Accordingly, recovery practices have fundamentally been based on empirical observations and subjective measures of well-being and perceived exertion or muscle soreness, rather than quantifiable markers of neuromuscular fatigue, skeletal muscle damage, endocrine responses or physical stress. An in-depth analysis of the neuromuscular, biochemical and endocrine responses to match-play provides insight into player responses to competition and the time-course associated with a return of those responses to pre-match baseline levels.

The significance of the present research is that the early detection of acute and short-term post-match manifestations of neuromuscular fatigue, muscle damage and catabolic endocrine responses to elite Rugby League match-play may avert delay in recovery following match-play and optimise subsequent on field performance. Early detection of neuromuscular fatigue and a compromised endocrine status has important implications for the design and implementation of training and recovery programs to improve the performance of all athletes involved in professional and amateur sport.

1.4 Research Questions

The present research will examine a number of questions associated with the examination of neuromuscular, biochemical, endocrine and physiological response of elite Rugby League players to the demands of match-play.

1. Can valid measurements of force and power be determined from the CMJ. (Experimental Study 1).
2. What are the most meaningful force-power-time measures that can be determined from the CMJ (Experimental Study 1).
3. What are the physiological demands and movement characteristics of players during elite Rugby League match-play? (Experimental Study 2).

4. What are the endocrine and biochemical responses of players during elite Rugby League match-play. (Experimental Study 3).
5. How does salivary cortisol, testosterone and the testosterone : cortisol ratio respond to elite Rugby League match-play and what is the value of these endocrine measures to monitor recovery post-match? (Experimental Study 3).
6. Is the CMJ an appropriate test to determine the force-power-time characteristics of elite Rugby League players? (Experimental Study 4).
7. Are any variables measured during the performance of the CMJ capable of detecting a change in neuromuscular performance and fatigue in NRL footballers? (Experimental Study 4).
8. Are CMJ performance variables of PRFD, PP and PF reliable indicators of neuromuscular fatigue in NRL footballers? (Experimental Study 4).
9. What impact does NRL match-play have on the neuromuscular fatigue and muscle damage markers in NRL footballers? (Experimental Study 5).
10. Can the characteristics of impact associated with collisions during elite Rugby League match-play be characterised for player monitoring purposes? (Experimental Study 5).

1.5 Research Progress Linking the Experimental Studies

The present research examined the neuromuscular, biochemical, endocrine and physiological responses of elite Rugby League players to competitive match-play. To achieve this aim, five experimental research studies were undertaken and are presented as chapters three, four, five, six and seven of the thesis. Each experimental study within the present thesis was designed to build upon the preceeding chapter to enhance our understanding of the demands of Rugby League match-play and develop the primary aim of the thesis. Muscular force and power have been determined to be important characteristics of elite Rugby League players, therefore the rational for Experimental Study 1 was to establish the primary force and power measures associated with CMJ and SJ performance using a functional measure of SSC exercise that could be implemented with a large group of players in an efficient manner. The relative contribution of the primary force and power measures associated with CMJ and SJ performance, namely PF, PP and PRFD were established and identified as the most appropriate variables of VJ performance for future studies to identify neuromuscular fatigue and the time course of neuromuscular recovery post-match.

Following the establishment of PF, PP and PRFD as the primary contributors to VJ performance in Experimental Study 1, an analysis of playing position-specific movement patterns during NRL competition was undertaken to establish the demands of elite Rugby League match-play using GPS

and accelerometer technology. Recent studies have examined the time-motion characteristics of semi-professional Rugby League match-play using video-based tracking methods, however no studies have examined the position specific movement and match-play specific physiological demands of NRL match-play using contemporary GPS / accelerometry. The rational for Experimental Study 2 therefore was to undertake the first multiple match position-specific analysis of elite NRL match-play in almost 10 yrs using GPS / accelerometer technology under 2009 match-play defensive and interchange rule structures.

Experimental Study 3 increased the scope of our understanding of the biochemical and endocrine responses of elite Rugby League players to competitive match-play. The rational for this novel study was to incorporate GPS / accelerometry techniques utilised in experimental study two while undertaking a simultaneous investigation of the pre- and post-match sTest, sCort, sT:C and plasma [CK] to quantify the demands of NRL match-play and examine the rate of recovery for a period of six days post-match. Further insight into the demands of elite Rugby League match-play was provided via an examination of pre- and post-match markers of neuromuscular fatigue in experiemental study four. Experimental Study 4 examined PF, PP and PRFD during CMJ and SJ that were determined to be the primary determinants of VJ performance in experimental study two to establish the change in SSC performance and the magnitude of change in these force-power variables to determine neuromuscular fatigue following elite Rugby League match-play. The PF, PP and PRFD measured during the CMJ and SJ were compared to the degree of change in plasma [CK] and endocrine measures to ascertain the correlation between dependent and independent variables associated with elite Rugby League match-play and the post-match recovery period. An additional rational for the Experimental Studies 3 and 4 was to determine whether plasma [CK], salivary endocrine and force-power measures during the CMJ and SJ could be used as objective markers of muscle damage, stress and neuromuscular fatigue experienced by elite Rugby League players pre, during and post-match.

One of the fundamental characteristics of elite Rugby League match-play that differentiates the sport from other football codes and contact sports is the degree of blunt force trauma and incidence of high velocity collisions during competition. The rational for Experimental Study 5 therefore was to further develop our knowledge regarding the demands of elite Rugby League match-play via examination of the relationship between pre- and post-match plasma [CK] and endocrine responses and the intensity, number and distribution of impacts associated with collisions during NRL competition. The collective results of Experimental Studies 2, 3, 4 and 5 may also be used to monitor individual player tolerance to training and competitive loads and should be considered when developing recovery and training plans over the course of an extended season of weekly elite Rugby League competition.

The research undertaken in the present thesis aimed to comprehensively investigate the neuromuscular, biochemical, endocrine and physiological responses of elite Rugby League players to competitive match-play. There are a number of novel aspects to each of the experimental studies presented as five individual chapters, including the determination of PF, PP and PRFD as the primary contributors to VJD during the CMJ, quantification of the position specific physiological demands of NRL match-play using GPS / accelerometer technology, examination of plasma [CK], sCort, sTest, sT:C and markers of neuromuscular fatigue pre- and post- elite Rugby League match-play and an examination of the biochemical and endocrine response associated with repeated blunt force trauma during match-play in the NRL. Independently and collectively, each of the five experimental studies presented in the present thesis represent a more robust investigation of NRL match-play than reported previously and contribute to the current understanding of the demands of elite Rugby League competition.

CHAPTER 2
OVERVIEW OF THE LITERATURE

2.1 PERFORMANCE CHARACTERISTICS OF RUGBY LEAGUE MATCH-PLAY

2.1.1 Physiological Demands of Rugby League Match-Play.

Despite the popularity of Rugby League in Australia and the professional status of players in the NRL, there is a paucity of research that has examined the physiological demands of elite players during competitive Rugby League match-play. At the elite level, Rugby League is a high intensity collision sport that requires high levels of muscular strength, power, flexibility, speed, agility, and aerobic and anaerobic capacities to complement individual and position specific skill requirements (24, 58, 92, 159, 169, 339).

Numerous studies have reported the anthropometric and physical characteristics of Rugby League players at the amateur (160, 161, 166, 168, 170, 171), semi-professional (15, 19-21, 93) and professional (14, 22-24, 59, 309) level. Other studies (58, 159, 169) have reported the applied physiology of Rugby League based on retrospective data relating to the physical attributes of players rather than the demands of actual match-play. Few studies have investigated the physiological demands of match-play in amateur (162), junior elite (144) and semi-professional (92) Rugby League players. No studies have investigated the physiological demands of match-play in elite players under current NRL interchange rule structures.

As expected, the mean HR, peak HR and the mean percentage of maximum HR (% HR_{max}) recorded during Rugby League match-play increased as the playing standard increased from amateur to semi-professional and junior elite levels (92, 144, 162). During amateur Rugby League match-play, Gabbett (162) reported players mean HR to be 152 beats · minute $^{-1}$ ($b \cdot min^{-1}$), equating to approximately 78 % of HR_{max}. The increased demands of semi-professional match-play resulted in an elevated mean first half and second half HR of 167 ± 9 and 165 ± 11 $b \cdot min^{-1}$ respectively (92) while junior elite Rugby League players mean HR was reported to be 172 $b \cdot min^{-1}$ (144), equating to 84 % and 93 % of their age specific HR_{max} respectively. Furthermore, semi-professional and junior elite Rugby League players were found to spend approximately 30 – 44% of match-play undertaking high intensity activities with HR > 85 % HR_{max} (92, 144). The estimated mean relative exercise intensity (% VO_2

max) of semi-professional Rugby League match-play was reported to be 81.1 ± 5.8 % VO_2 max (92). Collectively, previous studies using HR responses (92, 144, 162) have reported that Rugby League match-play placed substantial physiological demand on the aerobic and anaerobic energy systems (159).

To date, limited empirical data exist on the physiological requirements of competitive Rugby League match-play (92) and data that do exist are equivocal. Heart rate (HR) analysis has been reported as a proxy measure of VO_2 and energy expenditure due to the linear relationship between these parameters during submaximal exercise intensities (241). It is important to note that the estimate of VO_2 from HR is likely to overestimate oxygen consumption during high intensity exercise such as Rugby League match-play due to factors that may cause HR to rise independently of VO_2, namely heat, emotional stress, static exercise (366, 372) and elevated catecholamine levels during contact related team sport activities (120). Recently, HR monitoring systems have been developed incorporating algorithm-based predictive software to assess VO_2 and energy expenditure and add to the usefulness of HR based monitoring to quantify physiological responses to training and team sport competition (314). Limitations however are associated with the collection of HR data during high intensity intermittent exercise, such as Rugby League match-play and include the tendency for HR to be elevated beyond the expected HR-VO_2 relationship due to the influence of repeated blunt force trauma during physical collisions, isometric skeletal muscle contractions during scrums and tackling, thermal and psychological stress associated with competitive match-play (92, 120).

The physiological demands of elite Rugby League match-play under current limited interchange rules are unknown. Consequently, further studies examining the relationship between HR and VO_2 measured during intermittent high intensity contact sport are required. The development of portable GPS units designed for athlete tracking have provided an alternate valid and reliable data acquisition method to determine the physiological demands of match-play in real-time through HR monitoring software (111, 289). Investigation of Rugby League match-play incorporating portable GPS units provides extended scope for an improved understanding of the position specific physiological demands of competition to optimise training rationales and on-field performance.

2.1.2 Movement Patterns in Rugby League Match-Play.

Time-motion studies (246, 307, 308, 396) have been used to determine the movement patterns of Rugby League players during match-play. Early studies performed by Meir et al., (307, 308) investigated time-motion analysis of professional Rugby League match video recordings under a pre-existing 5m defensive rule prior to 1993 (307) and following the introduction of the 10 m defensive

rule in 1994 (308) requiring players who are not in possession of the ball to immediately retire 10 m from the play-the-ball at the completion of each tackle. Using notational time-motional analysis methods in real-time, these early studies (307, 308) revealed that the majority of Rugby League match-play for the hooker (84 %), front rower (87 %), half-back (92 %) and wing (95 %) (307) positions consists of low intensity activities such as standing, walking and jogging. The mean running distances reported for forwards and backs during match-play prior to the introduction of the 10 m defensive rule were 6647 m and 7336 m respectively (307). The mean distances travelled by Rugby League players during match-play may suggest a substantial demand is placed on the aerobic energy system during competition. The nature of Rugby League match-play however requires players to perform high intensity activities such as accelerating, decelerating, sprinting, jumping and withstanding physical collisions during offensive and defensive phases of play and thereby places considerable additional demand on the anaerobic energy system (307).

Following the introduction of the 10 m defensive rule, running distances increased to approximately 10000 m for forwards, representing an increase of over 3000 m from the 5 m rule and approximately 8500 m for backs, representing an increase of over 1000 m from match-play under the 5 m defensive rule (308). During matches played under the 10 m defensive rule, forwards were found to spend a greater percentage (3.3 %) of match-time participating in high intensity activities in comparison to matches played under the 5 m defensive rule (0.8 %) (308). An analysis of high intensity to low intensity activities (exercise-to-rest ratio) was also found to increase from 1:6 and 1:8 for forwards and backs respectively during match-play under the 5 m defensive rule (307) to 1:10 and 1:7 for hookers and front rowers respectively and 1:12 and 1:28 for half-backs and wingers respectively (308) during match-play under the 10 m defensive rule. While these early studies (307, 308) indicate the aerobic demands of professional players during match-play was increased with the introduction of the 10 m defensive rule, some (308) suggested the increased exercise-to-rest ratio may reflect an increase in the intensity of exercise when actively involved in play. Subsequently, the need for an extended recovery period between high intensity exercise efforts would be increased. While these early time-motion analysis studies (307, 308) of Rugby League provided insight into the fundamental activity patterns and distances covered during match-play, such studies were limited by small sample size, a failure to examine players from each playing position and the introduction of rule changes in subsequent seasons.

Recent studies (246, 396, 397) have added to our understanding of the physiological demands and movement characteristics of semi-professional and professional Rugby League match-play. In a preliminary study of elite NRL and semi-elite New South Wales Premier League (NSWPL) Rugby League players, elite players reportedly covered greater total distance and greater distance during high intensity running in comparison to semi-elite players. King et al., (245) undertook a time-motion

analysis using video recordings of professional Rugby League to quantify the characteristics and frequency of repeated bouts of high intensity exercise during match-play. Although limited by small subject numbers (n = 9) and generalised positional group classifications, namely Hit-up forwards (Front Row, Second Row and Lock Forwards), adjustables (Half-back, Hooker and Five-Eighth) and outside backs (Centre, Wing and Full-back), King et al., (245) reported no significant positional differences for relative time spent participating in high intensity exercise (15.9 % - 17 %). Mean exercise-to-rest ratios were 1:6 for hit-up forwards and outside backs and 1:5 for adjustables while mean work periods lasting 4 seconds (s) followed by rest periods of 21 s were reported (245). The longest period of continuous high intensity exercise completed during match-play was 27 s, 35 s and 22 s for outside backs, adjustables and hit-up forwards respectively, while the maximum number of high intensity exercise bouts in each of three matches analysed was 22 (245). To complete their analysis of professional Rugby League, King et al., (245) found the average number of tackles and hit-ups for outside backs, adjustables and hit-up forwards was 27, 35 and 51 respectively.

In a subsequent video-recording based time-motion analysis of professional Rugby League using the same number of subjects (n = 9), positional group classifications (n = 3) and matches (n = 3), King et al., (246) reported that outside backs and adjustables covered significantly ($p < 0.05$) greater distances than hit-up forwards (6265 ± 318 m, 5908 ± 158 m and 4310 ± 251 m respectively) during professional match-play. When the results were considered relative to time on the field however, there were no significant positional differences in distances covered. Maximum distances covered in any single match were 6486 m , 6082 m and 4579 m for outside backs, adjustables and hit-up forwards respectively (246). These results are substantially less than previously reported by Meir et al., (308) and may reflect less total time spent on the field by players in each positional group under interchange rules in the NRL in 2005. Note ably, hit-up forwards who were interchanged during the course of match-play reportedly spent approximately 21 min on the bench.

In addition to their analysis of the number of tackles performed, number of hit-ups and distance covered during match-play, King et al., (246) used a notational intensity of movement categorisation approach to log the frequency, distance covered and duration of match-play activities. Categories of intensity ranged from 0, which constituted no effort to 5, being the greatest level of effort under the following format: 0 (standing), 1 (walking), 2 (jogging), 3 (striding and lateral movements), 4 (tackling) and 5 (sprinting) (246). Movements in categories 0 to 2 were considered low-intensity movements for the purposes of match-analysis while categories 3 to 5 were considered to be high-intensity activities. When the percentage of time spent undertaking high-intensity activities was expressed relative to total on-field match participation, outside backs, adjustables and hit-up forwards completed 17.0, 15.9 and 16.5 % of match-play performing high-intensity activity respectively (246). Similarly, no significant difference was found in the relative percentage of time performing low

intensity activities during match-play was reported between positional groups with outside backs, adjustables and hit-up forwards completing 83.0, 84.1 and 84.5% respectively. The percentage of time undertaking low-intensity activities during match-play are similar to those reported by Meir et al (307) for forwards (84.3 % - 87.4 %) but not backs (91.9 % - 95.4 %) suggesting an increased involvement of backs in match-play.

The exercise-to-rest ratio during Rugby League match-play reported by King et al., (246) for outside backs and hit-up forwards was 1:6 and 1:5 for adjustables and are lower than those reported previously for adjustables of 1:7 to 1:12 and for wingers 1:28 (308). King et al., (246) reported 4 s of high-intensity activity was followed by approximately 21 s of low-intensity activity, which is less than the findings of earlier studies on Rugby League (308) that examined match-intensity where ranges of 4 s of high-intensity exercise was followed by 30 s to 80 s of low-intensity activity. The increased intensity of match-play reported by King et al., (246) is supported by other researchers (396) who found increased frequency of high-intensity activities during match-play in elite NRL and semi-elite NSWPL Rugby League players. While the variation in exercise-to-rest ratio during match-play may in part be due to modification of positional groups used for analysis, modification of interchange limitations and improvements in computer-based tracking systems, collectively, the findings of recent studies (245, 246, 396, 397) demonstrate that the physiological demands and movement characteristics of modern elite Rugby League match-play are considerably more demanding than previously reported (307, 308).

2.2 GLOBAL POSITIONING SYSTEMS (GPS)

2.2.1 Performance Analysis Using GPS Units

Quantification of the specific movement characteristics and physiological demands of Rugby League match-play is paramount for the development of sport-specific training programs and recovery protocols to optimise performance and potentially reduce the risk and incidence of injury (289). Most commonly, the practice of quantifying movement patterns during sports performance has been undertaken through notational time-motion analysis or the implementation of computer based tracking technologies in real-time, or post-match, incorporating video recordings with or without customised computer analysis.

Time-motion analysis has been conducted in various contact team sports including Rugby Union (118, 119, 124, 131, 303, 369), Australian Rules Football (115, 116, 452, 453) and Rugby League (246, 307,

308, 396). While traditional video tracking methods quantify player movement during competition, the use of varied and inconsistent categories to describe player movement patterns could have compromised information on the physiological demands and movement characteristics of match-play in Rugby League. Limitations of time motion analysis using match video recordings in Rugby League and other football codes have been reported (119, 123, 130). The labour intensive nature of retrospective video recording analysis and the failure to operate in real-time, may make such video analysis prone to measurement error and prolong assessment of player performance indicators (123, 134). Although a high degree of validity has been reported for estimation of total distance using traditional time-motion analysis methods (120, 368), poor compatability between notational and digitising methods of analysis have been reported with a 27.5 % difference in the estimation of time spent in work during field based sports (368). As more advanced technologies for performance analysis emerge, there is a need for a concomitant increase in the quality of evaluation and analysis of information so as to improve training practices and performance outcomes.

Recently, the development of portable GPS units designed for athlete-tracking have provided an alternate data collection method to determine the demands of training and competition in real-time (111, 267, 268, 289, 358, 432), with the potential to overcome some of the limitations associated with traditional methods of performance analysis. The GPS is a satellite-based navigation system made up of a network of 24 satellites in orbit around the earth. The GPS work anywhere in the world, 24 hr a day, and in all weather conditions. Each satellite is equipped with an atomic clock that synchronises with the clock in the GPS receiver and constantly emits information at the speed of light about the exact time to the GPS receiver (267).

Positional data of players wearing the GPS receiver is determined by comparison of the travel time of the radio frequency signals emitted from at least four orbiting satellites (267, 390). By comparing the time given by the satellite and the time within the GPS receiver, the signal travel time (displacement of the GPS unit) is calculated. The lag time that is determined by comparing the time given by a satellite and the time within the GPS receiver is used to determine the distance from the GPS receiver to the satellite by multiplying the signal travel time with the speed of light (267). By calculating the distance from the GPS receiver to at least four satellites, an exact three-dimensional position and altitude of the GPS receiver can be determined trigonometrically (389, 433, 443). For detail on calculations see Witte and Wilson (477). The GPS receiver compares the time a signal was transmitted by a satellite with the time it is received, the time difference tells the GPS receiver the distance to the satellite (434). By comparing this signal lag time from four satellites the GPS receiver can determine the position of the player during training or competition.

In most commercially available GPS systems, player speed profile data are determined via Doppler shift, i.e. measurement of the rate of change of the satellite signal frequency due to movement characteristics and relative speed between the satellite and the GPS receiver (389, 390, 434, 435, 443). Alternatively, speed can be determined from changes in the distance recorded by the GPS and the time difference between two logged positions (389, 443) to quantify the speed profile of athletes during the course of sports specific competition. In order to measure body acceleration, the GPS receiver contains an integrated tri-axis (x, y and z axis) accelerometer that measures accelerations and gravitational (G) force in three movement planes, namely forward:backwards, up:down and tilt left:right. The integrated accelerometer within the GPS unit measures acceleration and deceleration in ms^2 to determine the combined G-force as the sum of the G-force measured on each directional axis (189).

2.2.2 Validity and Reliability of Portable GPS in Sports

Originally, GPS technology was developed for the United States (US) military, however in the 1980's it became available for civilian use. To reduce the risk of the GPS technology being used by hostile forces, selective availability (SA) was a deliberate error embedded into the orbiting satellite network by the United States (US) Department of Defence. In 1999, the US Department of Defence reduced the deliberate error within the system, allowing for an increase in the accuracy of non-differential GPS technology (267). The resultant increase in accuracy of non-differential GPS technology is of considerable importance to the evolution of GPS to athlete-tracking methods. Non-differential GPS receivers, such as the GPSports SPI-Pro units used in experimental studies 2, 4 and 5 of the present research, are lighter, smaller, less expensive and require less complex data collection procedures than earlier GPS technologies, increasing the application of the non-differential GPS units to many sporting environments (289).

Recently, improved miniaturisation, enhanced battery life and increased sampling capabilities has lead to the establishment of the GPS athlete-tracking units as more convenient, time efficient and valid method to quantify movement patterns and physiological demands in sport. The GPS technology has been used to determine the movement patterns and physiological demands of athletes during training and competition in a range of sports, including Rugby Union (111, 211), Australian Rules Football (17, 91, 134, 474, 475), Cricket (356), Tennis (129), Soccer (28, 358), Orienteering (269) and Triathlon (38). Studies have employed several different commercially-available GPS brands, including: GPSports (89, 111, 134, 356, 474), Catapult (17, 356), Garman (267, 269) and Wonde Proud Technology GPS-BT55 (443). Currently there are two brands of GPS units regularly used in the NRL; GPSports and Catapult. Although there appears to be universal agreement that GPS

technology has considerable potential to describe and analyse the movement patterns and physiological demands of training and competition, limited data exist regarding the validity and reliability of current GPS technologies to quantify match-play characteristics in sports involving high intensity intermittent exercise (89, 129, 231, 289, 290).

Such is the nature of the rapid and constant evolution in GPS unit recording capabilities and applications, that early generation GPS units measured data at 1 Hz (SPI-10, GPSports, 2007) and were upgraded to 5 Hz (SPI-Pro) in 2009 and 15 Hz (SPI-**X**) in 2010. Most studies that have investigated the validity and reliability of GPS technology in team sports using GPS units with 1 Hz sampling capabilities and 100 Hz accelerometers (28, 89, 134, 289, 290, 443). To date, few studies (129, 231, 356) have examined the validity and reliability of GPS units that measure at 5 Hz and accelerometers > 100 Hz. Townshend et al., (443) concluded that a non-differential GPS system (1 Hz / no accelerometer) offered a valid method of assessing human locomotion and that the correlation between speed of a straight 60 m course and speed on a circular path of 10 m radius, measured by GPS and timing gates, was r = 0.99. Townshend et al., (443) concluded that the non-differential GPS system can provide a valid estimate of distance, reporting the mean estimated distance over a 100 m course was 100.46 m (r = 0.49).

Subsequent research (356) has incorporated advanced GPS micro technology to examine the validity and reliability of GPS devices during simulated Cricket activities. Using three commercially available GPS units (SPI-10 1Hz, GPSports; SPI-Pro 5Hz, GPSports; MinimaxX 5Hz, Catapult; Melbourne, Australia), Petersen et al., (356) examined 20 trials of cricket-specific locomotion patterns over a range of distances and running intervals performed by a single subject (n = 1). The validity (Standard error of estimate (SEE) 0.4 ± 0.1 to 3.8 ± 1.4 %) and reliability (CV 0.2 – 0.4 to 2.3 – 4.0 %) was established for all GPS units during walking and jogging longer distances (600 m to 8800 m), however larger errors were evident in sprinting shorter distances (20 – 40 m) for all GPS units with validity (SEE 2.6 ± 1.0 to 23.8 ± 8.8 %) and reliability (CV 1.6 – 2.8 to 23.2 – 43.4 %) respectively (356). Specifically, the validity of the different GPS units during walking to striding locomotion patterns ranged from 0.5 ± 0.2 to 2.1 ± 0.8 % for the SPI-10 unit in comparison to the SPI-Pro (SEE 0.4 ± 0.1 to 3.7 ± 1.4 %) and MinimaxX (SEE 1.7 ± 0.6 to 3.8 ± 1.4 %) units respectively. Larger error was evident during sprinting over short distances (20-40 m) for the SPI-Pro (SEE 2.9 ± 1.1 - 10.9 ± 3.9 %) and MinimaxX units (SEE 5.3 ± 2.0 – 23.8 ± 8.8%).

Similarly, the reliability of GPS estimation of cricket specific locomotion patterns was superior for longer distances. During walking to striding locomotor patterns over longer distances, the reliability of the SPI-10 was < 2 % and < 4 % for the SPI-Pro and MinimaxX units respectively. For high

intensity sprinting, data using the SPI-10 was not provided however the reliability of the SPI-Pro ranged from 2 – 13 % and 4 – 43 % for the MinimaxX units. Accordingly, using both the SPI-Pro and MinimaxX units, shorter sprints (20 m) tended to be less reliable than for longer (40 m and run-a-three) sprints. The major findings of Petersen et al., (356) indicated that the measurement of short sprint efforts using all types of GPS units should be viewed with caution whilst for longer distances at lower velocities of locomotion the SPI-10 and SPI-Pro and units underestimated (up to 4 %) whereas the MinimaxX units overestimated (up to 3%) cricket specific locomotion patterns. Petersen et al., (356) concluded that from a practicality perspective, GPS athlete tracking technology is superior to other workload monitoring techniques, however the accuracy and reliability was dependent on the GPS brand used and further improvements are required for a detailed analysis of high intensity efforts that are characteristic of cricket or indeed the repetitive shuttle running nature of Rugby League match-play.

The GPSports units used in the present research are claimed by the manufacturer to be 99 % accurate in continuous straight line running, and 96 – 97 % accurate in dynamic team sport situations with rapid changes of speed and direction (189). In a study of movement characteristics during Australian Rules Football, Edgecomb & Norton (134) found a 1Hz GPS system (SPI-10, GPSports) over-estimated distances by a mean of 4.8 % while Coutts & Duffield (89) compared different movement velocities between three different 1Hz GPS models concurrently from the same manufacturer (SPI-10, SPI-Elite and WiSPI, GPSports) during eight laps of a standard circuit designed to reflect the movement demands of team sport. Although only two moderately trained men participated in the study of Coutts and Duffield (89) mean circuit total distance was significantly ($p < 0.001$) different between each of the GPS units. However, all devices were found to be reliable (CV < 5 %) and were within 5 m of the actual lap distance. The CV for total distance (3.6 – 7.1 %), peak velocity (2.3 – 5.8 %), high intensity running (11.2 – 32.4 %) and very high intensity running (11.5 – 30.4 %) for all GPS devices examined by Coutts and Duffield (89) depicted the accuracy and reliability of the first generation of 1Hz GPS units for total distance and peak velocity during high-intensity, intermittent exercise. The results of Coutts and Duffield (89) however included small subject numbers (n = 2) and GPS units with a sampling frequency of 1 Hz and should therefore be viewed with caution in comparison to studies (305, 356) that have incorporated GPS units with higher sampling frequency (> 5 Hz) and larger subject numbers.

In an examination of GPS technology to assess player movement patterns in field hockey, MacLeod et al., (289) used a measured circuit of hockey-related shuttle and running movements of various speeds that was repeated fourteen times (total circuit distance = 6818m) to assess the validity of a 1Hz non-differential GPS system (SPI-Elite, GPSports). MacLeod et al., (289) utilised only one unit and reported the validity of distance and mean speed for four types of hockey specific shuttles, total lap

distance and overall total distance. Significant differences ($p < 0.01$) were found from the criterion distance during the shuttle runs, with mean underestimation of 1.2 % to an over-estimation of 0.08 % reported (289). The mean lap distances and total circuit distance were not significantly different from the criterion distance (mean overestimation of 0.04 % and 0.06 % respectively) suggesting that the GPS system offered a valid tool for measuring speed and distance during hockey match-play.

Similarly, Jennings et al., (231) incorporated a simulated team sport running cicuit that incorporated straight line and change of direction running to examine the validity and reliability of position, distance and speed data using GPS units in elite Australian Rules Football players (n = 20). To similate the demands of ARF match-play running patterns, players completed straight line running (10, 20, 40 m) at various speeds (walk, jog, stride, sprint), changes of direction courses of two different frequencies (gradual and tight) and a team sport running circuit over distances of 5 m to 40 m. Position and speed data were collected by each player wearing two GPS units (1 x 1 Hz and 1 x 5 Hz) simultaneously. The results of Jennings et al., (231) revealed higher sampling rate (5 Hz) improved validity regardless of distance and locomotion during straight line, change of direction and simulated acceleration and deceleration running patterns. The reliability of GPS improved as the distance traveled increased but decreased as speed increased regardless of sampling rate. In agreement with previous research (89, 134, 289, 356), the 1 Hz and 5 Hz GPS devices displayed acceptable reliability and validity for assessing total distance during longer duration running activities. Reliability of the GPS units over shorter distances of < 20 m however were poor (CV > 10 %) regardless of locomotor activity, running speed or sampling rate. Higher sampling frequencies improved the reliability during high speed measures when sprinting through change of direction courses, suggesting the 5 Hz GPS units are more suitable for use in team sports where changes of direction are prevalent (231). Caution is recommended when incorporating GPS and accelerometer technology to examine short, high speed running involving change of direction, however an increased sample rate improves the validity and reliability of GPS devices and supports the continued use of GPS technology to quantify movement demands during team sport training and competition.

Recently, the correlation between sprint performance over 15 m and 30 m using both a portable GPS device and timing lights during a 7 x 30 m repeated sprint ability test (RSAT) were examined to determine the validity and reliability of GPS technology to assess speed and repeated sprint ability (RSA) in physically active college aged subjects (n = 147) (28). The results of Barbero-Alvarez et al., (28) showed a significant correlation between peak speed measures using a 1 Hz GPS device (SPI-Elite, GPSports) and RSAT performance measured with timing lights for the 15 m ($r = 0.87$; $p < 0.001$) and 30 m ($r = 0.94$; $p < 0.001$) intervals respectively. Further, when the RSAT was repeated at least one wk apart, results demonstrated test re-test reliability of summated maximal speed (CV 1.7 %) and peak speed (CV 1.2 %) and 7 x 30 m RSA performance, suggesting the GPS device may be a

suitable measure of sprint performance characteristics in team sport athletes (28) such as elite Rugby League players.

2.2.3 Measurement of Movement Patterns and Physiological Characteristics During Match-Play.

The GPS unit (Figure 1) is worn in a purpose designed vest (GPSports, Australia) to ensure that range of movement of the upper limbs and torso was not restricted (Figure 2). Manufacturer guidelines (GPSports, Canberra, Australia) report the effective distance of the GPS units used in the present study for data collection as 200 m from the field of play. The GPS unit is worn in a padded mini backpack contained in the vest and positioned in the centre area of the upper back slightly superior to the shoulder blades at approximately the level of the first thoracic vertebrae (T1).

Figure 1. SPI-Pro GPS unit (GPSports).

To quantify the movement characteristics of match-play, commercially available GPS systems used predominantly in the NRL (GPSports, Catapult) incorporate measures of total distance travelled, work rate ($m \cdot min^{-1}$) athlete accelerations and speed profile characteristics in real time. A zone classification system of movement forms the basis of match-play analysis using manufacturer software (Team AMS – GPSports, Logan plus – Catapult), allowing six ranges of speed ($m \cdot sec^{-1}$/ $km \cdot hr^{-1}$) and HR ($b \cdot min^{-1}$) to be set and used for analysis. Zone 1 indicates the lowest effort or lowest velocity of movement with each zone progressively categorizing effort and movement intensity to Zone 6 which represents the highest effort and greatest velocity of movement (Table 1). The movement classification system used most commonly in Rugby League match-play analysis is based on locomotor activity classification methods used in Rugby Union (111). The frequency and duration of entry into each movement zone

has been reported to provide a more precise profile of activity patterns among playing position (forwards and backs) in intermittent sports (210).

Figure 2. Positioning of GPS unit during Rugby League match-play.

Figure 3. Heart rate (HR) chest strap position during Rugby League match-play.

Each movement zone (Zone 1 to Zone 6) may be sub-divided into two further locomotor categories to provide an estimate of player exercise to rest ratios. Standing / walking, and jogging are considered to be low intensity activities (< 12 km·hr $^{-1}$), while cruising, striding, high intensity running and sprinting are regarded as high intensity activities (> 12 km·hr $^{-1}$). The duration of each interval of low or high intensity exercise is divided by the duration in seconds of the subsequent rest interval to determine

exercise-to-rest-ratio for that passage of play. During match-play HR are recorded from each player by a commercially available HR monitor (Figure 3) in real-time, using chest straps for electrode placement (Polar Electro, Finland). HR signals are transmitted to the GPS unit positioned between the players' shoulder blades. The data are categorized into HR zones using Team AMS software (GPSports, Australia) (Table 2).

Table 1. Global Positioning System (GPS) speed zone classification using Team AMS software.

Zone	km·hr $^{-1}$	m·sec^{-1}	Movement Classification
1	0 – 6.0	0 – 1.6	Standing / Walking
2	6.1 – 12.0	1.6 – 2.7	Jogging (Low velocity running)
3	12.1 – 14.0	2.7 – 3.8	Cruising (Moderate velocity running)
4	14.1 – 18.0	3.8 – 5.0	Striding (Medium velocity running)
5	18.1 – 20.0	5.0 – 5.5	High velocity Running
6	> 20.1	> 5.6	Sprinting (Maximum velocity running)

The use of GPS to monitor training and match-play in professional Rugby League has become commonplace with the authorisation of GPS analysis during competition by the NRL in March 2009. However, a lack of published research in the sport of Rugby League has lead to uncertainty regarding the movement patterns and physiological demands of elite match-play. GPS technology has been used to determine the movement patterns and physiological demands of players during Rugby Union (111) and Australian Rules Football (91, 134, 474, 475) match-play. In particular, the AFL has commissioned time-motion research projects annually since the 2005 season and has established a large database of GPS match-play data collected each season (470-473).

Reports commissioned by the AFL have shown that the total distances covered by elite-level players during match-play have decreased from 12450 ± 1650 m to 12180 ± 1890 m from 2005 to 2008 (472).

Previous examination (116) of AFL match-play using video analysis to estimate total distances covered by players reported distances of between 10761 m and 18801 m with midfielders covering the greatest total distances (~ 17000 m) and forwards travelling the least distances (~ 13600 m). These estimated distances compare well with the results of others (332) that used computer tracking methods to determine the movement characteristics of AFL match-play (~17500 m) but are substantially greater than earlier (126, 197) reported distances of approximately 4000 m to 11000 m using manual player tracking methods.

Recently, Wisbey et al., (474) examined the movement characteristics of AFL match-play using GPS technology for each of three player groupings, namely forwards, nomadic, and defender positions. Typically, all players covered approximately 12 km per game irrespective of playing position, however nomadic players had a higher mean velocity (7.5 ± 0.6 $km \cdot hr^{-1}$) and covered 3.4 % more total distance (12.3 ± 1.9 km) in comparison for forwards (6.8 ± 0.6 $km \cdot hr^{-1}$; 11.7 ± 2.0 km) and defenders (6.8 ± 0.6 $km.hr^{-1}$; 11.9 ± 1.7 km) respectively. Approximately 65 % to total match time was spent either walking or slow jogging (< 8 $km.hr^{-1}$) during AFL match-play (474). Other researchers (91) have further substantiated the trend of reduced total running distance in recent years during AFL match-play (12939 ± 1145 m) using GPS technology. It is likely that changes in the amount of time spent on field by players under current unlimited interchange rule structures and increased skill levels of players at the elite-level has led to reductions in the total distance travelled during match-play. While there is considerable variation in the demands of Australian Rules Football and Rugby League, greater similarity in movement characteristics and physiological demands exists between Rugby Union and Rugby League match-play.

Only one study (111) has evaluated the physiological demands of elite Rugby Union using GPS technologies and considered the characteristics of impact associated with collision during competition. Using small subject numbers (n = 2) from a single match, the analysis is representative of a case study design involving Rugby Union match-play. The results of Cunniffe et al., (111) may therefore be questioned as an accurate representation of the physiological demands of elite Rugby Union match-play. Data reveal that on average, players covered an average of 6953 m (83.7 $m \cdot min^{-1}$) during Rugby Union match-play, with the back position player covering greater distance (7227 m; 71.9 $m \cdot min^{-1}$) than the forward position player (6680 m; 66.7 $m \cdot min^{-1}$) (111). During a total match-time of 83 min, on average players spent 72 % of match-play standing and walking, 18.6 % jogging, 3.3 % cruising, 3.8 % striding, 1.0 % high intensity running and 1.2 % sprinting (mean data, n = 2). The mean work-to-rest ratio was found to be 1: 5.7 for both subjects, indicating that for every one min of running, there was almost six min of lower intensity activity. The back position player achieved greater maximum running speed (28.7 $km \cdot hr^{-1}$), covered greater total distance sprinting (524 m), maintained greater

average speed (4.3 km·hr $^{-1}$) and completed a greater number of sprints > 20 km.hr^{-1} (total 34 sprints) in comparison to forward position player (26.3 km·hr $^{-1}$, 313 m, 4.0 km·hr $^{-1}$, total 19 sprints).

Table 2. Global Positioning System (GPS) heart rate (HR) zone classification using Team AMS software.

Zone	Percentage (%) HR maximum (HR_{max})
1	< 45
2	45.1 – 65.0
3	65.1 – 80.0
4	80.1 – 87.5
5	87.6 – 95.0
6	> 95.1

The work of Cunniffe et al., (111) found that the back position player participated in more anaerobic high-intensity activity interspersed with longer recovery periods in the lowest speed zones, whereas the forward position player spent more time in the moderate speed zones as recovery time between high-intensity activities. Cunniffe et al., (111) also reported that players exercised at 82 % and 85 % of VO_2 max for the back position player and the forward position player respectively. During match-play, the mean HR and HR_{max} was 172 b·min^{-1} and 199 b·min^{-1} for the back position player and 170 b·min^{-1} and 200 b·min^{-1} for the forward position player were similar, equating to ~ 88 % HR_{max} for both players, indicating that the metabolic demands of elite Rugby Union match-play are high (111). Cunniffe et al., (111) found that Rugby Union players receive a large number of impacts during the match, with positional differences observed between the intensity (total impacts > 7 G backs 66; forwards 170), distribution (total first half impacts: back 377; forward 461 / total second half impacts: back 401; forward 715) and total number of impacts received by the back position player (full match total 789) in comparison to the forward position player (full match total 1,274). Using integrated tri-axial accelerometer technology to determine the G force associated with match impacts, the forward was exposed to 60 % more impacts > 7 G and experienced three times as many severe impacts > 10 G in comparison to the back position player. Caution is recommended with respect to the interpretation of the work of Cunniffe et al., (111) due to the small number of subjects (n = 2) and a high degree of match to match variability in the demands of competition, however the present findings (111) support the inclusion of GPS determined impact characteristics to assess contact sport match-play and provides

insight into the intense nature of movement patterns and physiological demands of exercise that is characteristic of elite contact sport match-play and as such may reflect the requirements of elite Rugby League.

Recent studies (246, 396) have added to our understanding of the physiological demands of professional Rugby League, however as more advanced technologies for performance analysis emerge there is a need for a concomitant increase in evaluation and analysis of that information to improve training practices and reach desired performance outcomes. No studies have examined the influence of repeated collisions experienced by players during contact sports such as elite Rugby League match-play using portable GPS and integrated accelerometer technology. Investigation of Rugby League match-play incorporating portable GPS units therefore represents novel research regarding the demands of performance at the elite level, and provides scope for a better understanding of the position-specific physiological demands of elite Rugby League match-play.

2.3 FATIGUE AND ATHLETIC PERFORMANCE IN CONTACT SPORTS

2.3.1 Neuromuscular Fatigue

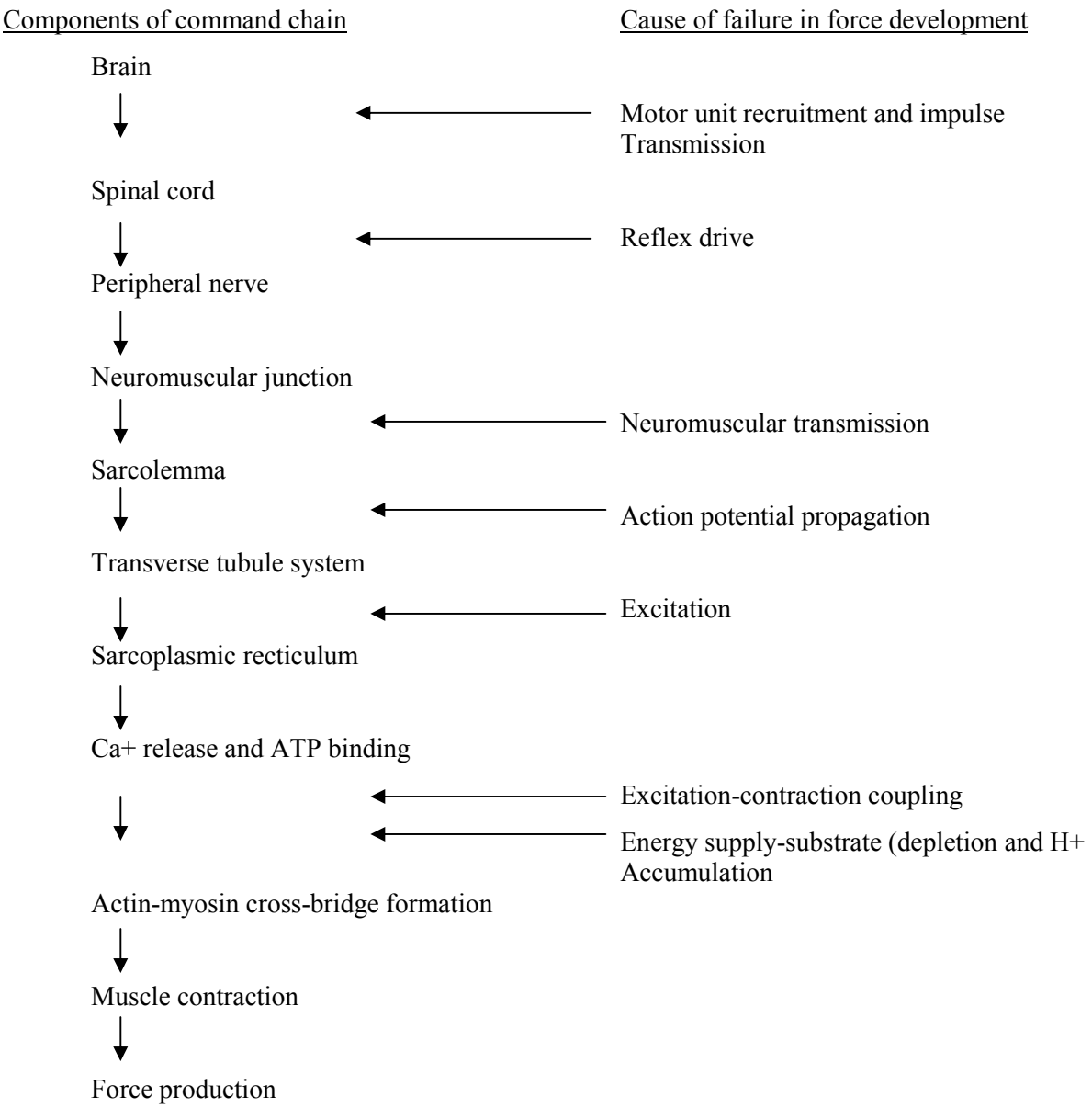
It is well understood that elite athletes are required to allocate training time to an intensity that mimics the sport-specific characteristics they experience during competition (170). Due to the demands of training and competition, athletes experience a constant cycle of "fatigue-recovery-adaptation", and as such, the monitoring of fatigue is important to determine appropriate training loads to maximize subsequent performance (154). Historically, fatigue has been defined in accordance with the varied subdisciplines associated with sports science, namely the divisions of physiology, psychology and biomechanics. Physiologists may consider fatigue as failure or dysfunction of a particular physiological system (375) while a psychologist may view fatigue as the perception or sensation of tiredness (239). For the purpose of the present review however, fatigue will refer to what may be considered to be a biomechanics view of fatigue, namely a reduction in the performance capacity of skeletal muscles during exercise that is characterised by a reduced ability to maintain or generate force (10, 174, 430). Neuromuscular fatigue is a complex phenomenon and has been described in humans as any exercise induced reduction in the maximal voluntary force or power produced by a muscle or muscle group (42, 45, 174) despite increases in perception of effort (411). The cause of

neuromuscular fatigue is regarded as multi-factorial and is influenced by the type of muscle contraction (36, 318, 352), the intensity and duration of the exercise (248, 280) including the rest period between contractions, (36, 127, 140) and the characteristics of the specific muscle or muscle group (36, 236, 283, 375).

Neuromuscular fatigue can develop at any location, or potentially in multiple locations during the activation-contraction chain (39, 288) (Figure 4). Traditionally, the mechanisms associated with neuromuscular fatigue are subdivided according to the site of the fatigue-specific decrement in force and are classified as central fatigue (α-motoneuron pool or above) and peripheral (motoneuron end plate or below) in origin (36, 423) and are task dependent in nature (141). The degree of skeletal muscle tension and resultant force produced by skeletal muscle during a maximal voluntary contraction (MVC) is determined by the motor unit (MU) firing frequency and pattern of MU recruitment (449). A progressive reduction in force and decreased tension development is evident in fatigued muscle (423) in conjunction with a loss of maximum force production (174, 198). Furthermore, a reduction in the RFD and inhibition of Ca^{2+} in the sarcoplasmic recticulum (SR) prolongs the Ca^{2+} transient leading to slower relaxation time and a reduction in skeletal muscle shortening velocity during exercise (151).

Fatigue studies (40, 141, 174) have demonstrated diversity in the causative factors underlying the fatigue-associated mechanisms that result in decrements in force production originating anywhere from the central nervous system (CNS) to cellular-level cross-bridge cycling (240, 248, 375). The major proposed mechanisms of neuromuscular fatigue production include inadequate excitation of motoneurons (174, 240), action potential transmission failure along axonal branch points (141), failure of the action potential to invade the synaptic bouton (240), failure of the action potential to trigger neurotransmitter release at the neuromuscular junction (45, 240, 288), failure of the action potential to propagate the full length of the sarcolemma (151, 240), failure of the action potential to invade the transverse tubule (T-tubule) system and SR to stimulate calcium (Ca^{2+}) release (46, 141, 190) and muscle contractile failure (46, 151, 240). The number of sites for potential failure of the neuromuscular system highlights the complex and diverse nature of fatigue. Despite studies (173, 174, 431) that have investigated the aetiology of neuromuscular fatigue, the exact location on the activation-contraction chain from the CNS to the level of contractile proteins where neuromuscular fatigue is controlled remains unclear. There is however, convincing evidence that both central and peripheral factors may independently and / or collectively be associated with decreased force production capability that is characteristic of neuromuscular fatigue during exercise (50, 198, 274, 278, 423).

Figure 4. The activation-contraction command chain and the major causes of muscle fatigue (Adapted from MacLaren et al 1989).



2.3.2 Central and Peripheral Components of Neuromuscular Fatigue

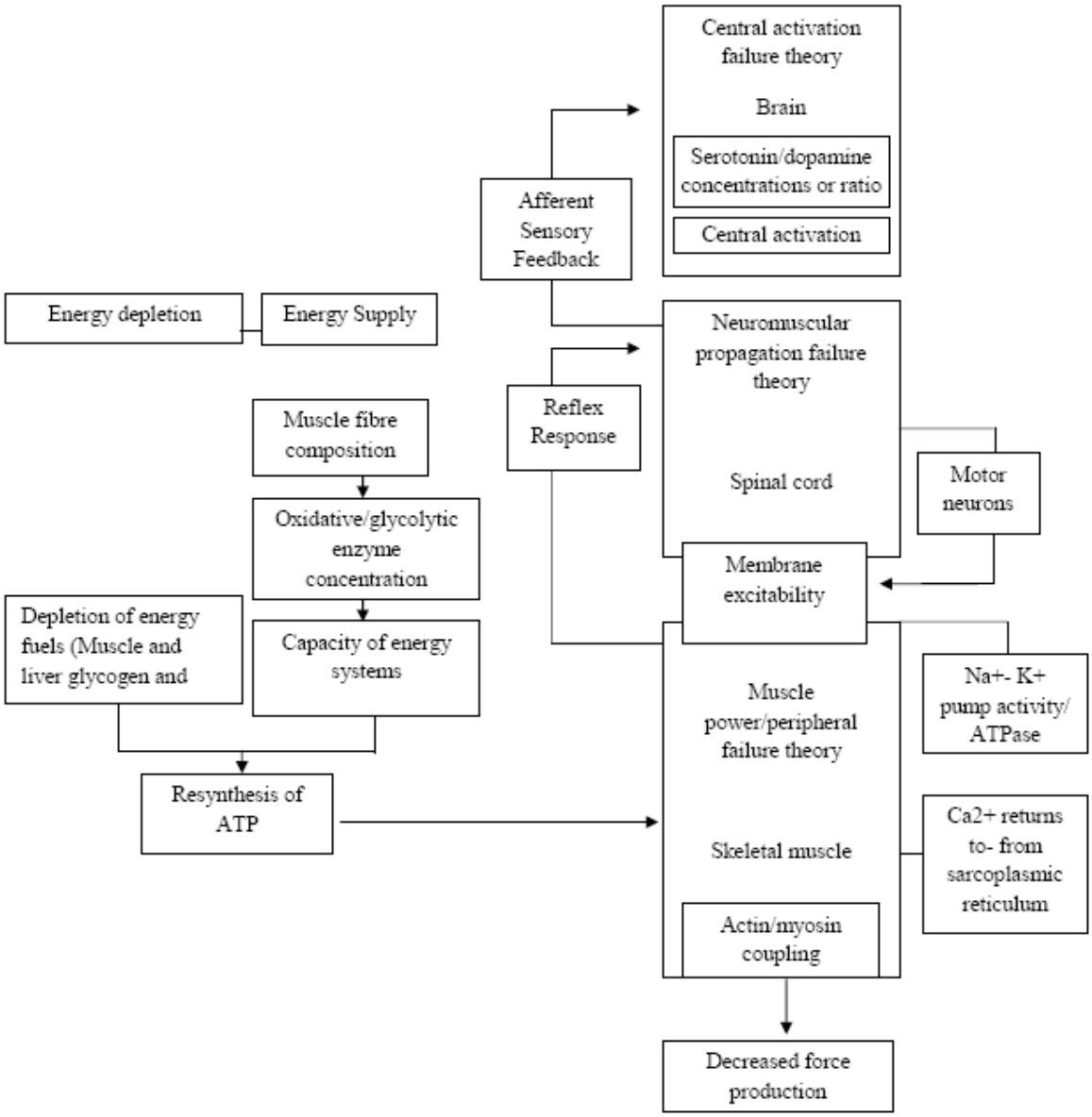
Central fatigue is defined as a progressive reduction in efferent motor command to active muscles that results in a decline in voluntary force or tension development during exercise (141, 174). Central fatigue can be demonstrated by an increase in the increment in force evoked by nerve stimulation techniques during maximum voluntary effort (37, 430) or an exercise induced progressive inability to perform a voluntary maximum activation of muscle during exercise (50, 174). Fundamentally, central

fatigue refers to conditions in which a decline in muscle force can be attributed to a reduced ability to drive motoneurons maximally and includes supraspinal fatigue that is associated with sub-optimal output from the motor cortex (174, 175, 431). Although the underlying mechanisms of central fatigue are complex in nature, and the definitive origin of central fatigue is inconclusive, slowing of MU firing rates has been measured in sustained and repeated maximal efforts (41, 44, 173, 430). The mechanisms that contribute to slowing or MU firing rates are fundamental to central fatigue and may be associated with a decrease in excitatory input, an increase in inhibitory input or a decrease in the responsiveness of the MN (430). In the case of reduced MU firing rate, voluntary muscle activation will fail to produce maximal force as a result of central fatigue (174) and may provide a protective mechanism to prevent exercise induced muscle damage (EIMD) (172, 374), homeostatic failure (374) or organ damage (330) during high intensity or prolonged exercise.

Although the actual mechanism of central fatigue remains unclear, intra-cortical inhibition (347) and neurotransmitter concentration changes, in particular increased serotonin, reduced dopamine and increased acetylcholine, have been attributed (2, 113, 114, 330) to a reduction in the rate of central neural drive and a negative influence on the excitement and recruitment of skeletal muscle during exercise. Clear contributions to loss of force during exercise have been attributed to spinal and supraspinal central nervous system (CNS) factors (Figure 5) during maximal contractions performed continuously, intermittently or superimposed on sub-maximal contractions (50, 430). During maximal voluntary and sub-maximal electronically stimulated fatiguing exercise conditions however, a loss of muscle force production in the presence of maintained muscle contraction characteristics (M-wave; Hoffman reflex [H-reflex]) indicate the development of fatigue due to mechanisms other than centrally mediated spinal and supraspinal factors (40, 50, 430).

An alternate rationale for neuromuscular fatigue during exercise is provided by peripheral fatigue mechanisms, referred to as exercise-induced processes that lead to a reduction in force production and that occur at, or distal to the neuromuscular junction (430). Peripheral fatigue is generally depicted via a reduced force response to electromyostimulation (EMS) pre- and post fatiguing exercise (154, 385). The decrement in force-generating capacity of skeletal muscle associated with peripheral fatigue may be due to altered cross-bridge cycle activity, excitation / contraction coupling failure, or failure of the action potential to propagate along the muscle membrane and into the transverse tubule system in the presence of sustained or increasing neural drive (46, 412, 428).

Figure 5. Neuromuscular fatigue model (Modified from Abbiss & Laursen, 2005).



Peripheral fatigue can be further divided into high-frequency fatigue (HFF) or low-frequency fatigue (LFF) (288, 423). High frequency fatigue, also known as Neuromuscular Propagation Failure Theory (2) (Figure 5) purports that the force-generating capability of skeletal muscle is determined by the muscles response to electrical stimulus (288) at the level of the sarcolemma (183, 190) or α-motoneuron (227). Briefly, increased sodium (Na^+) and reduced potassium (K^+) transmembrane gradients have been attributed to insufficient Na^+ / K^+ pump activation (190, 328) that alter intracellular [Na^+] and [K^+] and decrease action potential (M-wave) propagation into the T-tubule system, culminating in diminished Ca^{2+} release from the SR and a subsequent reduction in the activation of contractile elements involved in the generation of force and power (2, 141, 151, 190,

288). Alternatively, LFF has been described (154, 270, 422) as multifactorial fatigue resulting from moderate to high force, high intensity exercise involving repetitive eccentric or stretch shortening cycle (SSC) activities.

Low-frequency fatigue, also known as Peripheral Failure Theory (2) (Figure 5) denotes impairment in excitation-contraction coupling and attributes decrease force production of skeletal muscle during exercise to failure of the neuromuscular system at a muscular level (2, 288, 330). The Peripheral Failure Theory (2) proposes that decreased force production of skeletal muscle during exercise is due to peripheral fatigue that develops from alterations in the coupling mechanism between action potential and contractile proteins, or reduced Ca^{2+} release from the SR, leading to decreased Ca^{2+} binding to troponin C and the subsequent influence on actin-myosin interactions during cross-bridge cycling (2, 46, 127, 330).

Peripheral fatigue may result from simultaneous failure at a number of sites, however for any specific neuromuscular task, a particular site may be primarily responsible for any loss of force production ability of skeletal muscle, a concept referred to as task dependency of fatigue (46, 141). Task dependency of fatigue is an example of LFF and is characterised by a proportionately greater loss of force with low frequency muscle activation than with high frequency activation, a slow rate of recovery for force-generating ability that may be prolonged for hours, days or weeks, and persistence of low force production in the absence of marked electrical or metabolic disturbance (154, 234, 240). The fatigue determining features of LFF are in contrast to HFF, which is characterised by reduced force-generating capability of skeletal muscle at high frequencies of stimulation that is reversed by reducing the frequency of stimulation (43). Although the precise mechanism of LFF is unclear, both metabolite accumulation (hydrogen ions [H^+]; ammonia [NH^3] and inorganic phosphate [Pi]), energy substrate depletion (ATP; PCr and glycogen) (288) and a decrease in intracellular Ca^{2+} concentration have been suggested to play a role in the development of LFF (9, 46, 63, 76, 286, 465) during exercise. There is an absence of research investigating the role of central and peripheral fatigue during elite Rugby League match-play. The characteristic slow rate of recovery of force-generating ability that is associated with the manifestation of LFF may be an important consideration when examining neuromuscular fatigue in elite rugby League players participating in weekly match-play over a 26 week NRL regular season period.

2.3.3 Measurement of Neuromuscular Fatigue

Neuromuscular fatigue in humans has been measured objectively as an acute reduction of performance during exercise. The underlying physiological, neural and neuroendocrine mechanisms that determine the degree of fatigue related performance decrement have been the subject of a considerable volume of research (2, 9, 174, 288, 330, 375). Both central and peripheral components have been considered to contribute to the fatigue-induced impairment of exercise performance, however conjecture remains regarding the relative contribution of the potential sites of neuromuscular fatigue. Studies (50, 331, 360, 423) that have investigated exercise induced central fatigue in humans have incorporated twitch interpolation techniques to assess voluntary muscle activation and transcranial magnetic stimulation (TMS) of the motor cortex to identify supra-spinal fatigue via descending pathway activity (175, 284, 429). Alternatively, LFF has been induced using voluntary contractions (50, 274, 360) and incorporation of high-frequency (> 50 Hz) (50, 360, 422) and low-frequency (< 50 Hz) electromyostimulation (EMS) techniques (40, 46, 360, 422, 423). The distinction between HFF and LFF is potentially an important consideration to increase the understanding of neuromuscular fatigue in elite Rugby League players that perform repeated high intensity stretch shortening cycle (SSC) exercise and high anaerobic interval running workloads throughout the course of match-play.

Inadequate motor neuron (MN) excitation and the resulting decrease in MN output has been proposed as a fundamental mechanism of neuromuscular fatigue and has been associated with sub-optimal force-generating capabilities of the CNS during fatiguing exercise conditions (46, 240). Electromyography (EMG) is a measure of both the quality and quantity of electrical activity in the muscle and is an accepted method of determining functional and dysfunctional recruitment patterns during dynamic exercise (2, 277, 278, 360). During isometric maximal voluntary contractions (MVC), there tends to be a progressive decrease in EMG activity by the exercising muscles with a reduction in the firing frequency of MN and increased muscle relaxation time, recognised as fundamental contributors to reductions in muscle force production during exercise (2). On the basis that the amplitude of EMG signal reflects both the number of active MU and their firing rates (117), studies (34, 50, 83, 101, 360, 405) have incorporated a range of EMG parameters to quantify MU electrical activity and neuromuscular fatigue.

A study (236) examining fatigue responses of human triceps surae muscles during repetitive isometric MVC reported significant ($p < 0.05$) reductions in peak plantar flexion torque and EMG amplitude following 100 repetitive isometric MVC of the ankle plantar flexor muscles in full knee extension (KE) and 90° knee flexion (KF) positions. Plantar flexion torque in the KE position was greater and decreased more rapidly than in KF, while no significant difference was observed in EMG amplitude between muscles and joint positions during the fatiguing exercise protocol. Kawakami et al., (236)

concluded that the decrease in plantar flexion torque was attributable to both central and peripheral fatigue and the greater fatigability in the KE position was attributed to a greater contribution and more pronounced fatigue in the gastrocnemius muscle. Similarly, Boerio et al., (50) reported significant ($p < 0.05$) reductions in MVC torque in plantar flexor muscles following EMS-induced resistance exercise and attributed impaired contractile properties and EMG amplitude to both central and peripheral fatigue mechanisms. Although the use of various EMG parameters in the assessment of neuromuscular fatigue is well established (50, 360, 405), the incorporation of non-functional EMS and isometric MVC task analysis appears questionable for athletic populations. Accordingly, the validity of inferring dynamic fatigue characteristics from the performance of static tasks has been questioned (51).

In addition to the use of EMG to determine the characteristics of neuromuscular fatigue, mechanomyography (MMG) has been referred to as the 'mechanical counterpart' of EMG by non-invasively recording and quantifying the low-frequency lateral oscillations of contracting skeletal muscle fibres (31, 186, 345, 413, 415). It has been suggested (29, 30, 345) that the lateral muscle oscillations are generated by i) a gross lateral movement of the muscle at the initiation of contraction, ii) smaller subsequent lateral oscillations that occur at the resonant frequency of the muscle and iii) dimensional changes of the active muscle fibres.

Recent studies (100, 101, 405) have examined the MMG amplitude and frequency responses during maximal concentric, eccentric and isokinetic muscle actions. Sogaard et al., (405) reported that oscillations measured on the surface of the muscle are generally accepted to be determined by intrinsic mechanical events within the muscle, such as pressure waves created by muscle fibre dimensional change during each MU discharge. Although muscle temperature, stiffness and muscle fibre distribution may also influence muscle oscillation measured on the skins surface (346), Sogaard et al., (405) postulated that MU recruitment and the synchronisation of MU firing patterns as well as changes in these features may be revealed via MMG. Simultaneous measurements of EMG and MMG have been used to examine the dissociation between the electrical and mechanical components that occur during neuromuscular fatigue (34, 83, 101, 415). The amplitude of MMG signal has been related to MU recruitment and it has been suggested (345) that the MMG frequency content may provide information about MU firing rate. The amplitude of surface EMG signals however reflect muscle activation whereas during isometric muscle actions EMG is influenced by action potential conduction velocities of the active muscle fibres (34).

Contemporaneous examination of EMG and MMG signals may provide information regarding the potential differences that exist within, and among muscles for MU recruitment and firing rates used to increase force and or torque production during isometric and dynamic muscle contractions respectively

(34, 83, 101, 414). Coburn et al., (83) reported that during submaximal and maximal concentric isokinetic leg extensions, MMG and EMG amplitude for the vastus medialis muscle increased linearly with force, but there were no changes in MMG or EMG mean power frequency (MPF). During isometric muscle contractions, EMG amplitude for the vastus medialis (VM) muscle increased curvilinearly to 100 % MVC while MMG amplitude for the VM muscle increased to 80 % of MVC and then plateaued at higher torque levels. Although the MMG MPF for the vastus medialis muscle increased linearly with isometric torque, there was no change in EMG MPF. Coburn et al., (83) reported that the different torque related responses for EMG and MMG amplitude and MPF may reflect differences in motor control strategies that modulate torque production for isometric versus dynamic muscle contractions. In particular, Coburn et al., (83) suggested that for the vastus medialis muscle, concentric torque is increased through MU recruitment, with no change in MU firing rates. During isometric muscle action however, torque increased to 80 % MVC through a combination of increased MU recruitment and firing rates, whereas above 80 % MVC, MU firing rates alone determined torque production. Coburn et al., (83) concluded that isometric force production was modulated by a combination of MU recruitment and firing rate, whereas dynamic torque production was modulated primarily through MU recruitment with little or no change in MU firing rate. Collectively, the MMG and EMG signals provided evidence that the motor control (MU recruitment and MU firing rate) used by the vastus medialis muscle to modulate force production varied for isometric and isokinetic muscle actions (83).

Other researchers (34) have examined simultaneous measurement of EMG and MMG amplitude and MPF versus isokinetic eccentric torque relationships for the biceps brachii muscle. Beck et al., (34) found MMG amplitude increased from 10-60 % MVC and then plateaued from 60-100 % MVC, whereas MMG MPF increased linearly from 10-100 % MVC. Eccentric muscle torque related increases in MMG amplitude and MPF from 10-60 % MVC were associated with a combination of increased MU recruitment and increased MU firing rate (34). During 60-100 % MVC however, a plateau in MMG amplitude and increased MMG MPF suggested that MU recruitment may have expired at 60 % of MVC and further increases in eccentric isokinetic torque were due to increased MU firing rate (34). Beck et al., (34) concluded that for the biceps brachii muscle, simultaneous examination of the MMG and EMG amplitude and MPF versus eccentric isokinetic force relationships may provide information regarding the MU recruitment and firing rate strategies that are used to modulate eccentric isokinetic torque production.

Concurrent examination of MMG and EMG may provide information regarding MU recruitment and firing rates that determine force (or torque) production within an isolated muscle, or group of muscles during dynamic and isometric muscle actions. In a study (405) that examined MMG, EMG and force responses of the biceps brachii muscle before, 10 min and 30 min following 30 min of fatiguing

intermittent sub-maximal isometric elbow flexion, the verification of fatigue was established via significantly decreased MVC post-exercise. Sogaard et al., (405) found that intermittent contractions at submaximal level as low as 10 % MVC resulted in long term fatigue reflected in a decreased MVC for up to 30 min post-exercise. Although the long term fatigue was reflected in the EMG and MMG response to a 5 % MVC test, the change in MMG amplitude was more pronounced than the EMG change following 10 min and 30 min of recovery suggesting that MMG is most likely a useful parameter for detection of impairments in the excitation-contraction coupling occurring with MU activity during submaximal contractions (405).

Analysis of the EMG and MMG signals may contribute to our understanding of muscle-specific patterns of MU recruitment and firing rate that determine force production during isometric and dynamic muscle actions. Furthermore, the specific physiological mechanisms of fatigue that are detectable via alterations in MMG however remain questionable and may be associated with intra-muscular water content, thereby contributing to intra-muscular pressure and muscle stiffness that may influence MMG amplitude (405). Incorporation of EMG and MMG analysis during field testing protocols is however problematic and is restricted by the non-functional characteristics of the fatigue inducing exercise protocols used in this form of muscle assessment, such as isokinetic leg extensions and isometric elbow flexion movements. Logistical constraints are also associated with the incorporation of EMG and MMG measurement equipment required to determine the origins and mechanisms associated with neuromuscular fatigue limit the implementation of EMG and MMG analysis in applied research settings and sporting environments. Accordingly, it has been proposed (154) that a functional test capable of assessing LFF in athletes is necessary to appropriately monitor individual responses to training loads and enable practitioners to develop appropriate strategies to limit fatigue and optimise subsequent training and performance.

Prolonged cycling exercise to investigate the neuromuscular response to athletic performance has been used repeatedly (274, 275, 376, 412, 425) in conjunction with the force development characteristics of muscle immediately post-exercise and throughout the course of recovery periods of varying duration. The influence of 2 hr sub-maximal (65 % maximal aerobic power) cycling exercise on dynamic exercise in the form of maximal concentric, isometric and eccentric KE activity and EMS of the quadriceps muscles has been examined before and after exercise in trained cyclists and triathletes (274). Maximum peak torque was significantly ($p < 0.05$) reduced in all types of isokinetic exercise and at all angular velocities. The impairment of muscle function however was not specific to the type of contraction performed with reductions of 12-14 %, 12-13 % and 11-15 % for eccentric, isometric and concentric muscle actions respectively. The characteristics of muscular action potential of the vastus lateralis (VL) and VM muscles also changed after the 2 hr of sub-maximal cycling exercise. Lepers et al., (274) reported a significant ($p < 0.05$) increase in action potential duration (increased M-

wave duration) in the VL and VM muscles in addition to a reduction in EMG amplitude in both muscles, however the reduction in EMG amplitude was only significant ($p < 0.05$) for the VM muscle. Consequently, Lepers et al., (274) concluded that the reduction in force generating capacity of the VL and VM muscles after 2 hr sub-maximal cycling resulted from both reduced neural input to the muscles and peripheral mechanisms such as a failure in muscle membrane excitation, and in excitation-contraction coupling. While 2 hr sub-maximal cycling exercise proved effective in evoking an impairment of skeletal muscle function, the use of isolated isokinetic muscle activity to reflect the demands of non-cycling activities remain questionable, and particularly so for dynamic team sports such as elite Rugby League that requires players to perform frequent bouts of high intensity intermittent exercise interspersed with repeated blunt force trauma.

2.3.4 Neuromuscular Fatigue and Exercise

Investigating neuromuscular fatigue associated with dynamic exercise performed by athletes during sports performance has resulted in a range of fatiguing protocols and neuromuscular analysis procedures (275, 360, 398, 412, 422). Despite the number of studies investigating neuromuscular fatigue during exercise, few studies have examined the time course of EMG, MMG or functional decrements in neuromuscular performance following dynamic exercise incorporating the SSC. The effects of interval running on MVC KE and EMS-stimulated muscle contractions has been demonstrated via examination of the neuromuscular fatigue and recovery dynamics following high intensity intermittent running workloads (398). Following 5 x 300 m sub-maximal running efforts (target time 5 % lower than pre-recorded 400 m run time) separated by 1 min of low-intensity jogging, isometric MVC KE torque and muscle contractile characteristics maintained for 5 s via EMS of the quadriceps muscle were examined. Sustained KE MVC and EMS contraction of the quadriceps muscle were measured pre- and post-exercise, and then repeated at intervals of 3, 10, 20, 30, 40, 60 and 120 min post-exercise. Skof and Strojnik (398) found that interval running caused an acute decrease of EMS-stimulated muscle contractions however the maximum torque during MVC and the level of muscle activation remained unchanged immediately post-exercise and throughout the 2 hr recovery period. Skof and Strojnik (398) concluded that fatigue associated with high intensity intermittent running workloads was entirely peripheral and was induced by impaired activation-contraction coupling (LFF) and possibly a reduced efficiency of muscle impulse transfer along the muscle membrane (HFF). While the findings of Skof and Strojnik (398) indicated no change in MVC as a result of high intensity intermittent running interval workloads, it is questionable whether the exercise intensity and volume employed to cause neuromuscular fatigue was sufficient to replicate the requirements of competitive sports performance such as elite Rugby League match-play.

Incorporating EMG during dynamic exercise and semi-functional force-generating movements to assess neuromuscular fatigue may be of use in determining the origin of fatigue during exercise (34, 83, 236). Conversely, shortcomings remain regarding the functional specificity of isometric MVC and velocity limited isokinetic muscle contractions as valid measures of dynamic movement and muscle action velocities found in sports performance. Although isometric MVC is often incorporated into muscle force analysis methodologies to assess the entire motor pathway (430) and to determine the voluntary force-generating capacity of a muscle under relatively standard conditions (66, 127, 296, 360), movements involving isometric and isokinetic MVC portray little resemblance to muscle recruitment and activation patterns during a bout of dynamic exercise involving submaximal muscle contractions (66). Isometric force measures have also been reported to underestimate functional impairment of neuromuscular performance (66) and as such isometric MVC may be a poor measure of dynamic exercise performance. Furthermore, isokinetic muscle contractions may not replicate normal muscle contraction patterns that are characteristic of dynamic sports performance, such as acceleration, deceleration and ballistic running and jumping activities (66). Accordingly, the value of muscle contraction testing using isokinetic velocities to determine neuromuscular fatigue has been questioned (66).

Traditionally, neuromuscular fatigue has been examined using isolated forms of isometric, concentric or eccentric movements (174, 325). In order to analyse the functional loading of the musculoskeletal and neuromuscular systems during exercise, the mode of exercise during testing should replicate the requirements of training and or competition. Recent evidence suggests the incorporation of dynamic movements involving the SSC (306) provides a more specific examination of neuromuscular fatigue (250, 325) in these settings. Exercise involving the SSC incorporates metabolic, mechanical and neural elements of fatigue together with impairment of the stretch-reflex activation (325). Typically, the SSC involves a pre-activated muscle that is first stretched (eccentric action) and then shortened (concentric action) and is common to exercise such as running, jumping or hopping (250, 311, 325). Recovery following impaired SSC function and fatigue occurs in two phases identified by a significant initial decrement in SSC function and force production immediately post-exercise and a period of transient recovery followed by a decrement in performance, resulting in reduced SSC function some 48 to 72 hr post exercise (223, 250, 326). The immediate reduction in force production and SSC performance has been associated primarily with metabolic disturbances (e.g. metabolite accumulation, depletion of energy substrates and reduced mitochondrial respiratory control) (288) within skeletal muscle post-exercise while the secondary decline observed 48 hr to 72 hr post exercise has been attributed to inflammatory processes related to muscle damage (146).

Neuromuscular performance following short- and long-duration fatigue inducing SSC exercise protocols has been investigated (86, 99, 127, 184, 422, 423). Using a modified incline sledge

apparatus, Strojnik and Komi (423) examined neuromuscular fatigue following maximal SSC exercise incorporating a consecutive drop jumping protocol to 90 % of a pre-determined maximum VJH on a 33 kg sledge apparatus positioned on a gliding track inclined at 23° from the horizontal. Subjects were required to perform consecutive sledge drop jumps from a height of 80 cm until a jump height of > 90 % of maximum VJH could not be achieved. Following the SSC fatiguing exercise, EMS of the VL and quadriceps femoris muscle was used to induce a maximum isometric KE contraction and revealed a significant ($p < 0.01$) reduction in mean rate of force development while maximum force was maintained. Additional post-exercise supramaximal KE testing revealed significantly ($p < 0.05$) reduced maximum force and significant ($p < 0.01$) reductions in maximum KE force during low-frequency (20 Hz) and high-frequency (100 Hz) EMS stimulation. During sustained isometric MVC KE, mean EMG amplitudes in the VL and VM muscles demonstrated no significant change in maximum KE force production. Strojnik and Komi (423) concluded that impaired high-frequency action potential propagation was the predominant cause of fatigue as a result of what may be described as a semi-functional form of SSC exercise. Whether the mode of exercise used in the work of Strojnik and Komi (423) is representative of competitive sports performance is questionable, and particularly so for elite Rugby League match-play.

Our understanding of the effect of exercise and the contribution of neuromuscular mechanisms to muscle fatigue has been extended following a protocol of high-intensity uphill running exercise (270). Electrically evoked and voluntary contractions of KE MVC and EMG of the quadriceps muscles were analysed before and immediately following intermittent running exercise (10 x 60 s intervals) at 120 % of maximal running speed on a treadmill with an 18 % grade. Significant reductions in isometric MVC ($p < 0.05$) and MRFD ($p < 0.001$) were found post-exercise and the ratio between KE torques evoked by 20 Hz and 80 Hz stimulation also declined significantly ($p < 0.01$) after the intermittent exercise. The findings of Lattier et al., (270) are indicative of altered excitation-contraction coupling in the absence of central fatigue following high-intensity intermittent running on a treadmill. Although the results of Lattier et al., (270) identify a change in voluntary and evoked contractions as a result of high-intensity running activity, it is debateable whether their exercise protocol is representative of intermittent high intensity exercise sports sports competition such as NRL match-play.

The mode of exercise used to examine the requirements of sports performance should be functionally specific and simulate the characteristics of the actual competition. In practical terms, sports that are characterised by high intensity intermittent running or longer duration low intensity running activities should incorporate tests that require athletes to complete running protocols that replicate the intensity and duration demands of sports competition. Studies (150, 184, 327, 349) therefore have repeatedly examined the neuromuscular characteristics of fatigue during and after 10 km run performance. Nicol

et al., (327) examined the effects of long- and short-term fatiguing SSC exercise by incorporating 10 km running or fatigue inducing rebound jumping exercise on a sledge apparatus inclined at 25° from the horizontal. The fatiguing sledge exercise protocol included a series of 100 single maximal drop jumps performed every 5 s followed by continuous rebound exercise to 70 % of maximum jump height until exhaustion. Electrically evoked isometric MVC and EMG of the plantar flexor muscles were measured pre- and post-exercise followed by repeated measurement at 2 hr, 48 hr and 144 hr post exercise. Significant ($p < 0.001$) reductions in MVC were found in all subjects immediately post exercise and MVC remained significantly ($p < 0.001$) reduced for up to 2 days post-running and sledge jumping exercise. Nicol et al., (327) concluded that inflammatory processes associated with muscle damage resulting from the SSC exercise protocol may have influenced the post-exercise EMG and MVC changes observed. Furthermore, the findings of Nicol et al., (327) support the findings of others (270) that functional exercise incorporating the SSC are capable of detecting the presence of prolonged LFF resulting from running and jumping activities that are characteristic of sports performance. Despite the inclusion of running and jumping exercise protocols by Nicol et al., (327) and other researchers (270, 423), uncertainty remains regarding the appropriateness of electrically evoked isometric MVC testing to determine neuromuscular fatigue in athletes following sports performance.

The effects of 10 km running performance on neuromuscular fatigue has been demonstrated in trained (349) and untrained (150) subjects. Paavolainen et al., (349) monitored running velocity, ground reaction forces (GRF), ground contact time (GCT) and EMG activity during 20 m sprint performance before and after a 10 km time trial. During the course of the 10 km running exercise subjects completed 200 m of constant velocity running (4.5 $m \cdot sec^{-1}$ / 16.2 $km.hr^{-1}$) at the 3 km, 5 km, 7 km and 9 km stages of the time trial. Paavolainen et al., (349) found significant reductions in 20 m sprint performance ($p < 0.001$), prolonged GCT ($p < 0.001$), decreased GRF and reduced EMG during 20 m sprint immediately following 10 km run performance. The findings of Paavolainen et al., (349) suggest that a high volume 10 km running exercise protocol that included repeated bouts of moderate intensity running decreased the capacity of the neuromuscular system to generate force rapidly during 20 m sprint testing. The demands of elite Rugby League require players to perform up to 10 km of high and low intensity locomotor activity during match-play (246, 308) The results of Paavolainen et al., (349) therefore support the inclusion of explosive SSC exercise such as 20 m sprinting and CMJ testing to monitor neuromuscular fatigue in athletes following prolonged running exercise such as that experienced by elite Rugby League players during 80 min of match-play.

Further analysis of neuromuscular fatigue and force production following 10 km running performance has been provided by Finni et al., (150). Using a testing protocol similar to that described by Paavolainen et al., (349), 20 m sprint performance, GRF, GCT, plantar flexor MVC and EMG was

monitored before and after running 10 km at a constant speed of 3.5 ± 0.5 $m \cdot sec^{-1}$. The 10 km running test resulted in significantly ($p < 0.05$) decreased maximum running speed, reduced plantar flexor muscle MVC and EMG amplitude and a concomitant increase in GCT during the 20 m sprint test. The work of Finni et al., (150) indicates that the fatigue-induced impairment of the force generating capacity of the contractile component of the neuromuscular system may be revealed by tests measuring explosive SSC performance, such as 20 m sprint time, upper body throwing movements and horizontal or VJ testing.

Although isometric dynamometry remains a popular laboratory based method for assessing neuromuscular function of sports performance (360, 405), limitations associated with time consuming testing protocols, high cost and portability limitations of testing equipment has restricted the inclusion of isometric testing protocols in an applied sports performance setting. Furthermore, the recognition of dynamic strength and power as key determinants of contact sports performance (19-21, 24), has led to the CMJ and SJ becoming a widely used standard by which sports performance and neuromuscular fatigue is assessed (86, 216, 217, 261, 437, 485). The CMJ and SJ have been used as tests of the SSC and concentric muscle contraction to assess neuromuscular fatigue, athletic ability, identify athlete strengths and weaknesses and measure the effectiveness of training programs (55, 95, 205, 382). Performance of the CMJ and SJ by an individual is determined by a complex interaction of factors, including PF, PP, PRFD, the contribution of arm swing, sequencing and timing of segmental actions, and the coordination of the upper- and lower-body segments (221, 238, 370, 387, 467, 481). Additionally, the stretch-reflex, potentiation and visco-elastic properties of skeletal muscle in conjunction with upper and lower body segmental coordination during the CMJ and SJ have been shown to be similar to high intensity activities that are characteristic of sports performance (56, 295, 467, 481). Similarity between CMJ and SJ and the foot strike, stance and take off phases of running (56, 481), jumping and bounding during sports performance indicates that the CMJ and SJ may be pertinent for evaluating the demands of high intensity sports performance such as elite Rugby League match-play.

Various forms of the CMJ and SJ have been used to assess neuromuscular performance. A fundamental differentiation of CMJ and SJ technique is determined via the exclusion or inclusion of arm swing and lower limb countermovement during execution of the eccentric / preparation and concentric / take off phases of the respective jump technique (204, 207, 273, 393). For the purposes of the present review, a VJ that excludes arm swing and preparatory eccentric countermovement of the lower limbs will be referred to as a SJ and a VJ that includes arm swing and lower limb eccentric countermovement is referred to as a CMJ. The assessment of VJH, PP, PF and the RFD during the CMJ has been used extensively to assess sports performance and neuromuscular fatigue. Furthermore,

the incorporation of CMJ testing following SSC exercise (180, 184, 276, 348, 373, 460) and competitive team sports performance (11, 86, 228, 261, 437, 485) has become commonplace.

The recovery of maximal force and power during CMJ performance following intermittent (348) and prolonged (184) running has been examined. Paavolainen et al., (348) monitored a maximal anaerobic running power (MARP) interval treadmill running test (n x 20 s incremental running with 100 s between efforts), blood lactate concentration, RFD, EMG and CMJ height to assess the force-generating capacity and the rate of neuromuscular fatigue in endurance and sprint athletes. The CMJ was examined during the 100 s rest period between runs and 1, 2.5, 5 and 15 min post-exercise. The results of Paavolainen et al., (348) showed significant reductions in CMJ height ($p < 0.001$), EMG ($p < 0.01$) and RFD ($p < 0.05$) in sprint athletes during the maximal interval treadmill running. No significant changes in RFD, EMG and CMJ height occurred in the endurance group. Blood lactate was found to be significantly ($p < 0.05$) increased in both groups suggesting that reductions in muscle pH may have contributed to a decrease in force-generating capacity of skeletal muscle in sprint athletes. Paavolainen et al., (348) concluded that the ability of endurance and sprint athletes to perform explosive SSC exercise following fatiguing interval running was limited by an individuals metabolic capacity and identified the potential influence of metabolic limitations on neuromuscular fatigue and SSC performance.

The influence of metabolic factors (e.g. blood lactate accumulation and ATP, phosphocreatine (PCr) and glycogen depletion) on SSC performance raises the question of single CMJ versus multiple CMJ testing protocols to assess neuromuscular fatigue immediately following exercise and during the short term recovery period to determine the time-course of recovery post-competition. Numerous studies (54, 55, 87, 88, 99, 464) have used repeated CMJ testing to investigate the neuromuscular response to exercise. In an analysis of the reliability of measures obtained during single and repeated CMJ testing, Cormack et al., (88) reported that selected variables obtained during single and repeated CMJ were capable of assessing the acute and chronic effects of training and competition. Furthermore, the researchers (88) found that variability may exist between intra-day and inter-day results using single versus repeated CMJ protocols. For the single CMJ, measures of average force (AF), PF and PP were found to be highly reliable while flight time and relative AF were most reliable for repeated CMJ testing (88). Accordingly, the use of either single or repeated CMJ testing may be justified in determining force-power-time variables associated with SSC performance.

Additional research by Welsh et al., (464) examined the ability of single and repetitive (5 and 30 jumps) CMJ to identify the minimum number of jumps required to detect significant differences in force and power measures following eight days of intense military training. Interestingly, the primary finding of Welsh et al., (464) revealed that a single CMJ was sufficiently sensitive to detect changes in

lower-body physical performance. Welsh et al., (464) concluded that there was no advantage in using a repeated CMJ test over a single CMJ test for measuring lower-body force or power in either a laboratory or field situation for the purposes of monitoring changes in physical performance. On the basis of the available evidence, all studies contained in the present thesis examined lower-limb force and power measures incorporated single SJ and single CMJ testing protocols.

In a study that investigated the recovery of PF and PP following SSC exercise, Gomez et al., (184) examined single CMJ, knee flexion (KF) peak torque and isokinetic KF and KE endurance (50 repetition test) pre-, immediately post-race and 2 days after a 10 km running race. Gomez et al., (184) found significant ($p < 0.05$) reductions in KF peak torque, CMJ PF and the RFD during the CMJ immediately post-race. No significant changes were observed for CMJ PP at any stage post-race suggesting high-threshold MU required to produce explosive muscle actions were not affected by 10 km running performance (184). Significant ($p < 0.05$) reductions in CMJ PF occurred immediately post-race and remained reduced following 48 hr of recovery. The persistent pattern of reduced CMJ PF post-race suggests impaired contractile unit function and provides some support for the utilisation of CMJ testing post SSC exercise to measure neuromuscular fatigue following 10 km running performance. Similar reductions in peak KF and KE torque and CMJ performance have been reported following prolonged running over a duration of 2 hr (276) and confirms that CMJ measures can determine neuromuscular fatigue following functional SSC exercise. The prolonged reduction in the force generating capacity of skeletal muscle for a minimum of 48 hr following 10 km running (184) has important implications for coaches when determining the implementation of high-intensity or high-volume training regimes between weekly matches during regular season team sport competition schedules.

The functional impairments induced by prolonged, continuous activity, such as running and cycling have been well documented (150, 184, 274, 348), however less is known regarding the force and power development characteristics of the neuromuscular system following sports performance involving prolonged, high-intensity intermittent exercise. To this effect, Girard et al., (180) examined the changes in KE isometric MVC and PP during CMJ and SJ before, during and 30 min following 3 hr of tennis match-play. The 3 hr of tennis match-play did not alter CMJ and SJ PP during the course of the match however KE isometric MVC was significantly ($p < 0.05$) decreased post-match. The KE MVC remained significantly ($p < 0.05$) depressed 30 min post-match while PP during the CMJ and SJ was also found to be significantly reduced ($p < 0.001$) 30 min post-match compared to pre-match. The delayed reduction in CMJ and SJ PP 30 min post-match found by Girard et al., (180) may indicate the contribution of progressive inflammation associated with skeletal muscle damage and neuromuscular fatigue following prolonged exercise. The results of Girard et al., (180) support the role of functional exercise involving the SSC to measure neuromuscular fatigue following a prolonged bout of

intermittent high intensity exercise, such as that experienced by players during NRL competition and is therefore worthy of consideration to monitor neuromuscular fatigue following elite Rugby League match-play. Although determination of the mechcanisms of fatigue (central or peripheral) is important to increase our understanding of neuromuscular fatigue in sports, such understanding must be translated into practice. From a practical perspective, the incorporation of testing protocols that replicate sports specific movements should provide coaches and sports scientists with a more comprehensive overview of functional deficits' of individual athletes following training and competition.

2.3.5 Muscular Force, Power, Rate of Force Development and Sports Performance

Muscular strength, power output and the PRFD are considered key determinants of dynamic athletic performance, particularly in sporting events that require high force generation in short time periods (106, 324, 419, 420) and in sports characterised by frequent bouts of high intensity intermittent exercise such as elite Rugby League Football (20, 22, 24). Strength can be defined as the ability to produce force (394). Maximum strength is described as the voluntary PF of a muscle or group of muscles can exert as measured by the greatest load that can be moved through the concentric range of motion (386) or the greatest force possible under specified conditions (377).

Isometric dynamometry is a popular method for assessing neuromuscular function in athletes (3) as it permits the evaluation of strength related measures of PF and PRFD in a relatively low injury risk environment due to the absence of dynamic muscle contractions associated with the aetiology of muscle strain injury (344). The PF component of muscle function has been defined as the highest force produced during a maximal voluntary contraction, and is an index of maximal strength (292). The RFD is the development of maximal force in minimal time, and is typically used as an index of explosive strength (484). The reliability of isometric measures of neuromuscular function are established (292, 455), and several studies (238, 260, 292, 420, 479) have reported significant correlation between isometric PF and RFD, and activites involving dynamic muscle actions such as the VJ (260), sprinting (479) and sprint cycling (420). Other researchers (196, 230, 321, 364, 467, 480) however have failed to find a significant relationship between isometric measures of neuromuscular function and movements involving dynamic muscle actions or dynamic activities that require high RFD such as sprinting and jumping.

In an analysis of PF and RFD during isometric and dynamic sub-maximal and maximal mid-thigh clean pulls, Kawamori et al., (238) compared the relationship between force-time dependent variables

with CMJ and SJ performance in male collegiate weightlifters. Using a randomized counterbalanced testing protocol, Kawamori et al., (238) reported isometric PF (r = 0.82-0.87) and dynamic PRFD (r = 0.65-0.74) were significantly correlated with VJ, while isometric PRFD (r = 0.12-0.14) and dynamic PF (r = 0.27-0.72) had no significant correlation with VJ performances. Although a positive relationship between isometric PF and VJ has been reported by Kawamori et al., (238) and others (128, 420), the poor correlations between isometric PRFD and dynamic performance is consistent with research by others (196, 467) that found no significant relationship between isometric PRFD and CMJ and sprinting performance respectively.

Studies (292, 479) that have reported significant relationships between isometric PF and RFD have noted that the choice of knee joint angle during KE MVC testing can have a profound effect on the relationship between static measures of neuromuscular function and the performance of activities involving dynamic muscle actions, thereby challenging the validity of isometric testing methods to predict dynamic performance. Others (230, 321, 364, 480) have also reported limitations associated with functional specificity associated with isometric tests to predict dynamic performance. These results again emphasize the importance of functional specificity to the assessment of dynamic performance assessment. The ability to develop force rapidly during dynamic movements, but not during isometric muscle actions, may therefore be of greater importance to the performance of dynamic muscle actions involving the SSC and other dynamic movements that are characteristic of elite Rugby League match-play.

Dynamic PF, PRFD and PP have been identified as key strength and power measures that are fundamental to VJ and sports performance (260, 357, 400, 416, 418, 421). The VJ has been used extensively since the 1920's as a training and sports specific assessment modality of neuromuscular performance in athletes given the similarity of many sports specific movements and activities to the jumping movement (205, 382). Recently, the VJ has become an important inclusion in talent identification, pre-participation screening and long term athlete development models for the purposes of athlete profiling. Accordingly, the VJ has been found to be a reliable predictor of successful performance in sports such as American Football (300), Rugby League (20, 21, 24) and Soccer (476). In studies (21, 24) that have compared lower body strength and power characteristics of professional and college-aged Rugby League players, Baker et al., (21, 24) reported significantly ($p < 0.05$) greater measures of PF, AP and PP for professional players during one repetition maximum (1RM) squat and SJ tests. Baker et al., (21, 24) concluded that dynamic measures of strength and power may be used to discriminate between elite and sub-elite Rugby League players, with greater strength and power performance characteristics in elite Rugby League players.

Multiple versions of the VJ and the manner in which the VJ is performed have become fundamental factors in training program design and testing regimes for elite and sub-elite athletic populations. The CMJ and SJ are two common tests that have become popular due to the reported capacity of these tests to discriminate contractile characteristics of the lower limb musculature and the effect of muscle pre-stretch via the stretch shortening cycle (SSC) in athletes (295, 301). The SJ is commonly used to determine isolated concentric force and power development of the lower limbs (107, 467) whereas the CMJ has been used to measure reactive strength and slow SSC ability due to the eccentric-concentric nature of the preparatory and take-off movements (107, 387). Typically, the CMJ technique results in greater VJ height (VJH) compared with the SJ technique (251) due to the influence of upper body arm swing involvement that increases the total work of the lower limbs during the jumping phase (48, 204, 207, 273, 393). The combined effect of arm swing and the utilisation of the SSC of the lower limbs during the preparatory phase of the CMJ enhance VJ performance by allowing greater force to be developed during the concentric phase of the jump (48, 49).

In an examination of the influence of upper limb activity on lower limb force, power and work during the VJ using force plate and high speed camera movement analysis methods, Hara et al., (204) compared SJ performance with and without arm swing. Hara et al., (204) found significantly greater VJH ($p < 0.01$) and total work ($p < 0.01$) of the lower limbs during a single SJ testing protocol which was attributed to additional load placed on the legs due to arm swing, resulting in an increase in takeoff velocity when compared to VJ without arm swing (204). Bobbert & Cassius (48) explained greater VJH during the CMJ by active state development in the preparatory countermovement leading to greater force and work during the concentric phase of the movement. The SJ technique by comparison is characterised by active state generated during the propulsion phase only. Similarly, Lees et al., (273) reported increased centre of mass height and velocity on takeoff resulting from elevation of the upper limbs and resultant energy generation during the early phase of the jumping movement that was transferred to the lower limbs during the later stages of the CMJ.

Further analysis of the effects of arm swing and countermovement during vertical jumping has examined techniques of the VJ that involved no arm swing and no countermovement, no-arm swing and countermovement, arm swing and no countermovement and arm swing with countermovement on the vertical position and velocity of the centre of mass while jumping on a force plate (207). Both countermovement and arm swing techniques significantly ($p < 0.05$) increased jump height while arm swing also contributed to increased vertical GRF and PP in comparison to VJ movement without arm movement or countermovement of the lower limbs. The results of Hara et al., (204) and Harman et al., (207) are consistent with the results of others that have reported improvements in jump height, increased total lower limb work (273) and increased PF and PP (393) during single CMJ and SJ protocols incorporating arm swing and lower limb countermovement. The mechanism(s) by which

concentric force may be augmented by a preceding eccentric agonist stretch may be due to utilization of stored elastic energy, a myototic reflex, muscle-tendon interactions facilitating a maintenance of optimal length of the agonist and favourable concentric contraction velocity for force production, or optimisation of skeletal muscle activation patterns or development of a higher active state of skeletal muscle at the commencement of the concentric action (48, 70, 108).

Performance of the VJ is determined by a complex interaction among factors, including the PF developed by the musculature involved, the RFD, and the neuromuscular coordination of the upper and lower body segments (221, 384). To measure the contribution of PF, RFD and neuromuscular coordination of the upper and lower limbs a number of protocols and devices have been used, including the utilisation of contact mats, position transducers, V-scopes, accelerometers, rotary encoders, yardsticks and force plates (70, 107, 207, 279, 295, 416). The use of force plates to measure force and power from vertical GRF during VJ performance is common in laboratory settings (196, 238, 299, 416, 419) and is considered the "gold standard" for accuracy and precision of direct measurement of force and power parameters (295, 329, 392, 450). Access to force plates outside of the laboratory setting however has been limited for practitioners in the field due to the high cost of portable units, software requirements and the accepted standard for force measurement incorporating hard-wired floor mounted strain-gauge systems that restrict VJ force and power analysis to clinical testing facilities (461). Recently, the development of affordable and portable force plates that provide valid and reliable measures of force-time data during jumping tasks has improve the availability of force plate technology for testing in the field and for large groups of athletes (461).

Vertical jump height is commonly used by sports performance professionals as an alternative to direct measurement of maximal force and power (67, 212, 266, 357, 392). Accordingly, regression equations have been formulated to estimate peak and average leg power from jump height, body mass and / or reach height (18, 67, 205, 232, 384, 392). The Lewis Equation and its simple linear nomogram was devised to estimate leg power based on an athletes body mass, VJH and reach height (155). However, recent evidence has challenged the Lewis Equation on the basis that the PP calculated was an indirect estimation based on the force of gravity on the downward phase of the VJ from the peak jump height (205). Harman et al., (205) reported that the Lewis Equation substantially underestimated power during the VJ by determining average power (AP) and not PP produced by the subject. Subsequent equations (67, 212, 266, 384) have been developed with a view to improving the validity, reliability and accuracy of regression equations to determine power output during VJ testing. Limitations associated with small subject numbers, inconsistency and variation in VJ technique employed and the influence of gender have raised questions regarding the validity of predicting PP and AP on the basis of VJ height (13, 105, 187, 469). Furthermore, the use of the term "power" as a mechanical construct

to indicate maximal exercise performance is unclear with strength qualities such as RFD, impulse and explosive strength being suggested as a better predictors of athletic ability and performance (105).

Power is the rate of doing work (P = force x distance / time) and can be expressed as the product of force and velocity (P = force x velocity) (237, 420) that can be calculated as an average over a range of movement (ROM) or as a peak measure of performance. Muscular PP has been designated as the maximum potential product of force and velocity and is demonstrated as the highest power output achieved during a given movement (357) or the highest instantaneous power over a range of movement under a specific set of conditions (176, 420). Muscular actions that maximise power production include activities in which a movement sequence results in maximum achievable velocities. Accordingly, tasks requiring acceleration, deceleration, direction change and jump related movements rely on intermittent periods of high power output (324). Recent work (295) has shown that tests involving the SSC are valid and reliable tests for estimating leg power during CMJ and SJ in physically active men. The relationship between measures of power and performance for the lower body are well documented (70, 105, 106, 299, 418) however the manner in which power has been measured and methodological variations in research make comparisons between studies difficult. Notwithstanding these limitations, the ability of an athlete to optimise muscular power remains an important factor in determining sports performance (105) and particularly so for elite Rugby League players during match-play.

For many sports including elite Rugby League match-play, successful performance is coupled with high levels of strength (19, 21, 23, 106, 419, 421). During CMJ performance, not only is there a considerable force and power requirement, but force must be exerted at a rapid rate to facilitate optimal sports performance (299). The RFD is an index of explosive strength and reflects the capacity to exert maximal force in minimal time (484). The RFD has important functional significance in rapid and forceful skeletal muscle contractions during activities such as sprinting, throwing and jumping, which typically involve muscle contraction times of < 250 ms (1, 324, 467). In contrast, the time to reach maximum force in most human skeletal muscle is > 250 ms (199). Therefore, during rapid acceleration, deceleration or change of direction movements that are characteristic of sports performance, short skeletal muscle contraction times may not permit maximal force to be reached. As a result, the early increase in RFD becomes important to produce a higher level of force during the initial 100-200 ms of muscle contraction (1). The RFD may be considered to be more specific than other force-time measures (e.g. PF, AF, TPF) in athletes because in most sports, the time available to produce force is limited to < 250 ms (105).

Although RFD has been shown to be an important performance variable (176, 199, 467, 468), with athlete development models such as that outlined by Siff (395) indicating that the expression of

explosive strength as a key element in athlete progression to elite levels, others (195, 292, 450) have reported a poor relationship between RFD and the VJ. Indeed, Marcora et al., (292) found no significant correlation between RFD and VJ performance measured during an isometric MVC in a horizontal squat position and during VJ on a force plate. The absence of a significant correlation between RFD and the VJ may however be due to methodological inconsistencies and confounding factors associated with the measurement of RFD. Confounding factors include separate tests (450) when examining the relationship between RFD and the VJ and the inclusion of both male and female subjects in the assessment of RFD and VJ performance (195). Recently, Kawamori et al., (238) reported a strong ($r = 0.65 – 0.74$) albeit non-significant correlation between dynamic RFD and VJ performance. The absence of a significant correlation between RFD and VJ may have been due to small subject numbers (n = 8) resulting in low statistical power. Pryor et al., (364) also observed dynamic PRFD tests to be superior to isometric PRFD tests in the assessment of dynamic muscular function while Wilson et al., (468) reported a significant ($p < 0.05$) relationship between concentric only RFD tests, namely the SJ and dynamic squat performance.

Vertical jump height has been used widely to predict power during the CMJ (205, 232, 384), however it may be that the direct assessment of alternate variables, such as PP, PF, TPF and the RFD may allow greater scope for determining the characteristics of neuromuscular fatigue during CMJ performance. One of the key elements of athlete monitoring is the implementation of testing protocols that either directly represent or share characteristics of specific sports performance. Accordingly, the analysis of CMJ using portable force-plate technology is a test that provides valid and reliable information regarding PF, PP and PRFD of the lower limbs during SSC exercise that is characteristic of elite Rugby League match-play. No studies have investigated the influence of elite Rugby League match-play on force and power variables during the CMJ to assess their usefulness as measures of neuromuscular fatigue. Monitoring of force and power variables associated with CMJ performance may therefore be a valuable assessment tool to monitor fatigue and recovery in elite Rugby League players.

2.3.6 Neuromuscular Fatigue and Team Sports Performance

The CMJ is commonly used to assess the SSC and athletic performance. There are however limited data on the CMJ to determine the effect of competitive team match-play on neuromuscular fatigue (11, 217, 228, 261, 437, 485), and particularly so for contact sports such as Rugby League, Rugby Union, Australian Rules Football (86, 87) and American Football (216). Those data that are available are conflicting (86, 216, 217, 437). In an investigation of performance changes during college American Football match-play, Hoffman et al., (216) examined SJ and CMJ performance of “starters” and “non-

starters" before, and at the completion of each quarter of play throughout a single match. The results identified a non-significant reduction in SJ and CMJ PRFD in both groups during match-play while PF and PP during the SJ were significantly ($p < 0.05$) reduced during the first two quarters of match-play starters and non-starters. From the second quarter to the completion of the fourth quarter of the match SJ PF and PP significantly ($p < 0.05$) increased in both groups. During the CMJ, non-starters exhibited significant ($p < 0.05$) reductions in PF and PP during the first three quarters of the match. No significant declines in PF were seen in starters during any stage of match-play however a significant ($p < 0.05$) reduction in PP was found in starters at the completion of the second quarter of the match. Interestingly, a return of PF and PP to pre-match levels at the completion of the match was reported for all players. Reductions in PF and PP measures in starters during the first quarter of the match suggest that concentric only fatigue during the SJ tends to occur relatively quickly during American Football match-play. Alternatively, when performing SSC exercise in the form of the CMJ, American Football players tended to be able to maintain force and power performance to a greater extent. Hoffman et al., (216) concluded that localised metabolic fatigue associated with elevated blood lactate concentration may have occurred prior to the onset of central fatigue and had a positive effect on neuromuscular performance.

Comparison of the characteristics of neuromuscular fatigue during American Football and Rugby League match-play may however be limited. While American Football players are likely to experience heavy collisions and periods intermittent high-intensity exercise during match-play, there are fewer total blunt force episodes in comparison to elite Rugby League match-play. The fewer total blunt force episodes combined with reduced running volumes and extended rest periods between competitive efforts may have contributed to the maintenance of PRFD, PP and PF during American Football match-play. Furthermore, while the development of concentric only force and power produced during SJ may be characteristic of linemen during American Football match-play, there is a relative absence of isolated concentric muscle action during Rugby League match-play. Some argument may be considered regarding muscle actions of forwards during scrummaging, however the infrequent nature of scrums in the NRL suggests the effect of this sports specific activity on concentric force and power to be minimal. The results of Hoffman et al., (216) do however highlight the transient nature of metabolic disturbances (e.g. lactate accumulation, depletion of energy substrates and phosphate) during contact sport match-play and provide support for allowing sufficient recovery time post-exercise prior to PF, PP and PRFD testing to facilitate the analysis of neuromuscular fatigue in athletes without the residual influence of metabolic factors contributing to localised muscle fatigue.

To further investigate the impact of contact sports performance on the acute and short-term neuromuscular responses (recorded as absolute measures and relative to body mass) to competition, Cormack et al., (86) examined single and repeated (5 jumps) CMJ 48 hr pre-match, pre-match, post-

match and at 24 hr intervals for up to 120 hr following an elite Australian Rules Football (ARF) match. The results of the study (86) found single CMJ flight time, mean power, relative mean power, relative mean force, flight time : contraction time and repeated CMJ flight time displayed substantial decreases from pre- to post-match (decrements of -1.5% to -16.7%) and remained substantially reduced 24 hr post-match. No single or repeated CMJ data was reported 48 hr post-match however single CMJ mean power, relative mean power and repeated CMJ flight time was substantially reduced 72 hr post- AFL match-play. The results of all single CMJ performance variables at 96 hr and 120 hr post-match were reported to be trivial or unclear. Only repeated CMJ flight time was found to be substantially reduced 120 hr post-match. Acute reductions in post-match mean power and relative mean power may reflect a combination of central fatigue in the form of reduced central drive, and peripheral fatigue in the form of an impairment in action potential propagation over the sarcolemma (HFF) or impaired excitation-contraction coupling (LFF) (173, 174). Substantial decrement in single CMJ relative and mean power in conjunction with reductions in single and repeated CMJ flight time until 72 hr post-match is indicative of LFF and may reflect delayed recovery of the neuromuscular system in elite ARF players. Interestingly, the most remarkable finding of the research of Cormack et al., (86), as noted by the researchers themselves, was the lack of significant change in CMJ force-power measures in response to ARF match-play. Considerable variation in total running volume, sprint profile characteristics and the incidence of repeated blunt force trauma during ARF and NRL match-play however makes comparison of post-match neuromuscular characteristics questionable.

Relatively more studies (11, 217, 228, 261, 437, 485) have investigated the effect of soccer match-play on neuromuscular performance and fatigue with contrasting results. In an examination of isometric KE and KF MVC, contractile RFD and CMJ performance, Thorlund et al., (437) found no significant change in PF, PP or RFD during the CMJ when measured pre-, post- and 3-5 days post elite youth soccer match-play. Non-significant reductions in isometric KE RFD accompanying significant ($p < 0.05$) reductions in KF and KE isometric MVC were found post-match, indicating impaired mechanical function of skeletal muscle and decreased efferent neural drive, however the functional performance of the CMJ was not compromised post-match. Thorlund et al., (437) hypothesised that the lack of relationship between contractile RFD and MVC torque post-match may have been due to lower overall match-play intensity in youth soccer players and non-significant reductions isometric RFD. While measures of isometric MVC demonstrated impaired neuromuscular function in elite youth soccer players post-match, the influence of low-intensity match-play raises questions regarding the comparison of the findings of Thorlund et al., (437) to high-intensity explosive exercise that is characteristic of elite Rugby League match-play.

Additional analysis of soccer match-play has yielded similar results regarding the absence of compromised CMJ performance in elite female (261) and elite male (217, 485) soccer players. In an

examination of match-induced patterns of fatigue in elite female soccer players, Krustrup et al., (261) assessed repeated 30 m sprint ability, CMJ performance and the Yo-Yo intermittent test of endurance before and following competitive match-play. Post-match, significant reductions ($p < 0.05$) in repeated 30 m sprint performance provides some evidence that intense intermittent exercise, such as repeated sprint activity, is attenuated following soccer match-play in elite female soccer players. In contrast to reduced 30 m sprinting ability however, CMJ performance was not compromised by the soccer match, indicating the physiological mechanisms provoking fatigue vary with different forms of exercise. Krustrup et al., (261) speculated that transient metabolic disturbance toward the end of soccer match-play, rather than impaired neuromuscular performance, may have contributed to a decrease in the performance of intense intermittent exercise without influencing CMJ performance.

Consistent with the findings of Krustrup et al., (261) others (217) have reported no significant reductions in PF or PP during SJ and CMJ performance in "starters" and "non-starters" immediately following intercollegiate level soccer match-play in comparison to pre-match values. When players were re-assessed 24 hr post-match however, significant ($p < 0.05$) reductions in PP and PF during the CMJ, and PF during the SJ were found in starters. Significant correlations ($p < 0.05$) were also observed between playing time and PP during CMJ and SJ ($r = - 0.49$ and $- 0.57$ respectively) and between playing time and PF during SJ ($r = - 0.51$) performance when examined 24 hr post-match. The results of Hoffman et al., (217) show that force and power during the CMJ and SJ appear to be maintained for the duration of soccer match-play but decline significantly within 24 hr of match completion. The delayed reduction in neuromuscular performance may coincide with inflammatory processes associated with muscle damage during soccer match-play and may have important implications for examining neuromuscular fatigue following elite Rugby League match-play. Further, the work of Hoffman et al., (217) suggests that decrements in PP are more sensitive to movements involving the SSC and monitoring of neuromuscular performance should be extended beyond 24 hr post-match to determine recovery and a return to pre-match functional status following match-play.

In contrast, others (343) have reported significant reductions in CMJ performance immediately after simulated soccer exercise protocols and for up to 3 days following soccer match-play (11, 228). Using a soccer specific intermittent exercise test (42 min duration) that included maximal and sub-maximal SSC exercise and frequent acceleration and deceleration activities using a non-motorised treadmill, Oliver et al., (343) found significant ($p < 0.05$) reductions in CMJ and SJ in youth soccer players. No significant difference was found between CMJ and SJ performance following the soccer specific intermittent exercise protocol. There was however a tendency for greater reductions in performance of the CMJ that utilised the SSC in comparison to concentric only SJ testing. The findings of Oliver et al., (343) support for the incorporation of functional testing in the form of CMJ analysis to detect decrements in neuromuscular performance. The young age of subjects and the absence of any

influence of a competitive match-play environment, in the form of multi-directional running and an absence of repeated high velocity blunt force trauma experienced by Rugby League players however, questions the usefulness of the findings of Oliver et al., (343) for meaningful translation to the demands of elite NRL match-play.

In addition to the assessment of acute decrements in CMJ and SJ performance, the time course of recovery from neuromuscular fatigue following elite soccer match-play has been examined (11, 228). Andersson et al., (11) implemented an experimental design that investigated CMJ, isometric KF and KE MVC and 20 m sprint performance following two soccer matches conducted over a period of four days. Subjects were tested 3 hr before, immediately after and at intervals of 5, 21, 27, 45, 51, 69 hr after the first match (pre-match two) and immediately following the second match (74 hr post-match one). Sprint, CMJ performance and isokinetic strength were all significantly ($p < 0.05$) reduced immediately following the first match. A finding of particular interest for the management of athletes during the short term post-match recovery phase was the return of 20 m sprint times to baseline 5 hr after completion of the first match. Peak isokinetic KE and KF strength were significantly ($p < 0.05$) reduced for 27 hr and 51 hr respectively following the first match. Following both matches CMJ performance remained significantly ($p < 0.05$) lower than baseline values at all testing intervals, including 69 hr post-match one (pre-match two) regardless of recovery intervention protocols. Andersson et al., (11) reported that variation in the recovery rate of performance measures in the study may have been influenced by the presence of inflammatory markers associated with muscle damage and differences in the muscular work, and skeletal muscle coordination and activation patterns between sprint, CMJ and isokinetic KF and KE activity. The prolonged decrease in CMJ performance 69 hr post-match despite recovery of KE and KF strength suggests the influence of additional mechanisms, such as impairment of the SSC component that is indicative of neuromuscular function, may also contribute to delayed recovery of CMJ following soccer match-play. The findings of Andersson et al., (11) support the assessment of CMJ to determine the time-course of recovery of athletes following high-intensity intermittent exercise involving maximal and sub-maximal SSC activity that is characteristic of elite Rugby League match-play.

Further support for the inclusion of functional performance measures to quantify neuromuscular fatigue recovery following soccer competition has been provided by Ispirlidis et al., (228) in their examination of CMJ, single 20 m sprint and maximal strength testing of elite male soccer players. In a comprehensive investigation of the post-match recovery period, subjects underwent testing pre- and post-match followed by subsequent testing at 24 hr intervals for up to 144 hr post-match. The results of Ispirlidis et al., (228) found that functional performance deteriorated for between 24 hr and 72 hr post match with significant ($p < 0.05$) decrease in CMJ for 24 hr accompanied by significant ($p < 0.05$) reductions in 20 m sprint and maximal squat for 72 hr post-match. Ispirlidis et al., (228) attributed the

decrement in CMJ, 20 m sprint and maximum strength testing post-match to be consistent with structural damage to skeletal muscle associated with repeated high-intensity eccentric exercise during rapid acceleration and deceleration that is characteristic of soccer match-play. The findings of Ispirlidis et al., (228) supports the viewpoint that training should be closely monitored for several days post-match to optimise recovery and facilitate subsequent performance.

The evidence regarding the ability of SSC tasks such as the CMJ to detect neuromuscular fatigue and performance decrement following team sport match-play is limited, and those data that do exist are conflicting (11, 86, 216). The availability and functional specificity of CMJ testing using portable force plate technology and the ability to test large groups of athletes in a single session however has increased the use of CMJ testing in professional sports. To date, no investigation has examined the influence of elite Rugby League match-play on CMJ to assess neuromuscular fatigue during competition, or during the post-match recovery period. Current evidence supports the inclusion of CMJ testing to monitor neuromuscular fatigue following team sport match-play. The high intensity, intermittent nature of elite Rugby League match-play that includes frequent maximal and sub-maximal SSC activity and blunt force trauma is expected to cause considerable acute metabolic / peripheral fatigue in conjunction with prolonged central fatigue during the post-match recovery period. Accordingly, analysis of neuromuscular fatigue in elite Rugby League players represents an innovative and novel strategy to determine subsequent training loads, quantify decrement in the ability of players to tolerate training and establish the time course of recovery following match-play.

2.4 ENDOCRINE INDICES OF FATIGUE, SPORTS PERFORMANCE AND RECOVERY

2.4.1 Endocrine Markers of Fatigue and Recovery

Examination of endocrine responses to competitive contact sport performance (86, 87, 137, 215, 216) and during the post-competition recovery period (137, 138, 259) has been the subject of considerable investigation for several decades and has become common practice in professional sports. Studies (25, 95-97, 219, 287) have investigated the endocrine responses to intensified training and competition periods and the influence of a pre-competitive taper to identify overreaching, the early signs of overtraining and subsequent performance decrement. Recently, endocrine analysis has become an increasingly popular method of monitoring the post-competition recovery phase in professional sports (12, 86, 90, 110, 137, 259) to assist sports science and coaching staff to make decisions regarding the planning and implementation of training load for subsequent performance. A variety of physiological, biochemical and endocrine markers have been used to monitor acute and chronic responses to exercise and competition (75, 258, 320). In particular, testosterone and cortisol have been identified as reliable markers of the endocrine response to training stress and sports performance (86, 201, 254, 353).

Testosterone is the primary anabolic marker for protein signalling (410) and muscle glycogen synthesis (218). Normal serum values of testosterone typically range from 14.0 to 28.0 $nmol \cdot L^{-1}$ or 4.0 to 8.0 $ng \cdot L^{-1}$ in men (281). The most active form of testosterone is in the unbound or free form which accounts for approximately 2 % of all testosterone (281, 342). The remainder of testosterone is bound to albumin (approximately 38 %) and sex hormone-binding globulin (SHBG) (approximately 60 %) (142, 233, 281, 388). The 40 % of testosterone that is not bound to SHBG is available for metabolism while only the unbound or free form of testosterone is considered the most biologically active (193, 281, 312, 342). The synthesis and secretion of testosterone is indirectly controlled by the hypothalamus stimulation of the pituitary gland to secrete leutenizing hormone (LH) and follicle-stimulating hormone (FSH) which in turn activate the ledig cells of the testes to secrete testosterone (156, 158, 281). Despite highly individual and variable secretion patterns, circadian rhythms of testosterone in men have been reported previously (85, 112, 256, 281, 297) and have found the highest concentrations of testosterone in the early morning (~ 0800 hr) followed by a progressive reduction of 30 - 40 % throughout the day to reveal the lowest concentrations of testosterone in the late afternoon – evening (~ 1600 hr) (85, 112). Testosterone may play a role in several metabolic processes, including the reduction of cortisol induced glyogenolysis via an increase in muscle glycogen synthesis and increased protein synthesis to combat the proteolytic effect of glucocorticoids during exercise (218,

380). A substantial body of evidence has revealed that the response of testosterone to exercise is dependent upon the duration, intensity and type of exercise, and will be considered further in the present review.

Cortisol is considered an important stress hormone that acts antagonistically with testosterone to mediate catabolic activity and play an important role in metabolism and immune function (142, 229). Cortisol is a principle glucocorticoid in humans and is secreted from the adrenal cortex in response to hypothalamo-pituitary axis (HPA) mediated secretion of adrenocortiotrophic hormone (ACTH) in response to the stress of exercise (258, 442). Normal plasma concentrations of cortisol typically range from 138 to 635 $nmol \cdot L^{-1}$ in men (254). As a lipophilic steroid hormone, Cortisol is released into the circulation and bound to plasma proteins, namely corticoid binding globulin (CGB) (approximately 80-90%) and albumin (approximately 8 - 15 %) (258, 342, 350). The free fraction of circulating cortisol constitutes only approximately 10 % of the total hormone concentration (258, 342) and represents the bioactive fraction (that is, cortisol not bound to CBG) of cortisol (192). The metabolic actions of cortisol include the promotion of gluconeogenesis (218, 229), stimulation of lipolysis in adipose cells, increasing protein degradation and decreasing protein synthesis in skeletal muscle (142, 229, 258). The concentration of circulating cortisol throughout the day is dynamic and is influenced by circadian rhythms with peak values reported approximately 1 hr after waking in the morning and decreasing thereafter throughout the day (122, 442, 466). In physiological terms, cortisol is reportedly a reflection of the neuro-endocrine systems response to the stress during exercise (323) and a marker of the endocrine response to competitive high intensity combative sports (137, 149).

Testosterone and cortisol play crucial roles in the regulation of protein metabolism and muscle mass and reportedly vary in opposite directions in response to exercise, producing a decreased free testosterone and cortisol ratio (T:C) when training and competitive demands are increased (137, 218). An antagonistic relationship between anabolic and catabolic hormones has been reported (137), suggesting that a reduction in testosterone coupled with elevated cortisol to produce a catabolic endocrine status that may result in decreased physical performance (254). Elevated cortisol levels and a corresponding increase in glucocorticoid receptor binding has been shown to decrease protein synthesis and negatively influence skeletal muscle force production via a reduction in contractile proteins or neurotransmitters stimulated by testosterone (152, 254). The balance between the proteolytic action of cortisol and the anti-catabolic activity of testosterone increases skeletal muscle uptake of amino acids and the rate of protein synthesis thereby determining the rate of muscle hypertrophy or atrophy (282).

The T:C therefore has been postulated as a useful measure to reflect the balance between anabolic and catabolic tissue metabolism (4, 8, 26, 218, 258, 454) and subsequently has been suggested as a marker

of training stress and recovery rate following exercise (4, 95, 147, 218, 319, 378). In the case of an increase in testosterone, a decrease in cortisol, or both, would indicate a potential anabolic status in athletes and reflect a state of performance preparedness. Alternatively, an increase in training stress has been associated with a decline in testosterone with a simultaneous increase in cortisol, producing a reduction in T:C values (4, 252, 417). Elevated levels of testosterone have previously been linked to successful performance during strength and power tasks while diminished testosterone and increased cortisol, producing a decreased T:C, have been linked to overtraining, a reduction in exercise and sports performance and training-induced central fatigue (74, 158, 194, 254, 316, 454). Consequently, the T:C has been used to examine the anabolic:catabolic endocrine profile of athletes from contact sports (12, 86, 137, 215), however the response of testosterone and cortisol to Rugby League match-play is unreported.

2.4.2 Measurement of the Testosterone and Cortisol Response to Exercise

Numerous studies (26, 157, 216, 254, 294, 353) have examined the endocrine response of athletes to training, competition and testing and in particular have found testosterone and cortisol to be valid and reliable markers of training stress and fatigue. Historically, the most commonly used laboratory analysis procedures implemented by exercise and sports scientists to determine the endocrine response to training and competition in athletes has involved the analysis of a variety of bodily fluids, including serum, plasma, urine and saliva. Limitations regarding the impracticality of serial blood collections throughout daily training activities, the stress of venipuncture itself influencing cortisol levels and the inability of urinary measures to assess rapid changes in cortisol have been reported (192). To facilitate the sample collection process in an elite sporting environment, the availability of a sensitive and reliable measure of endocrine status in response to training and competitive demands is highly desirable. In particular, an easily administered and non-invasive sample collection procedure is ideal for team sports that are conducted over prolonged time periods with weekly competition such as is the case in the NRL. Accordingly, the ability to measure steroid hormones such as testosterone and cortisol non-invasively in saliva has created opportunity for sports scientists to increase the scope of athlete analysis and monitoring to improve sports performance.

Hormones enter saliva via passive diffusion and ultrafiltration (235). In general, serum and salivary levels of protein hormones are not well-correlated due to the protein-bound nature of hormones in serum thereby making the hormones too large to reach saliva in the absence of active transport mechanisms (235). The lipid soluble characteristics of steroid hormones such as testosterone and cortisol however enables passive diffusion and ultra filtration of the unbound (free) form of the hormones to enter the saliva, thereby enabling the biologically active form of testosterone and cortisol

to be detected in saliva (235). Further, salivary levels of testosterone and cortisol are not altered by variations in saliva flow rate (steroid hormones are dialysed through salivary epithelia rather than secreted with saliva due to the liposoluble properties of the steroid hormones) (75, 367, 457), increasing the potential utilisation of salivary hormone analysis during exercise that may result in reduced salivary flow rate.

Monitoring steroid hormones such as testosterone and cortisol in saliva rather than urine, serum or plasma has several well documented advantages for applied sports science researchers. The non-invasive nature of saliva collection eliminates stress responses associated with blood collection techniques, such as venipuncture, thereby reducing hormone shifts and facilitating the process of multiple sample collection protocols (102) that are commonly implemented in elite sports to monitor performance and recovery. The make-up of salivary testosterone (sTest) has been shown to be 78 % free testosterone in comparison to serum free testosterone constituting only approximately 4 % due to the absence of SHBG in saliva (242). In contrast, salivary cortisol (sCort) corresponds to approximately 35 – 45 % of serum free cortisol levels due to very low CBG content in saliva and the conversion of cortisol to cortisone via the enzyme 11 β-hydroxysteroid dehydrogenase in the salivary glands (235, 342). Salivary levels of testosterone and cortisol have been found to accurately reflect the biologically active form of the hormones in serum (446, 458) and exhibit a more dynamic response to intense exercise (102, 192). The use of saliva testosterone and cortisol may therefore provide more physiologically relevant data (192) for athlete monitoring purposes in comparison to traditional and complex serum analysis methodologies.

Numerous reports (112, 233, 242, 312, 322, 458) have shown high correlation between salivary and serum free testosterone concentration in male and female subjects. Vittek et al., (458) investigated the relationship between salivary and serum free testosterone versus salivary and serum total testosterone and found significant correlations ($p < 0.001$) of $r = 0.97$ and $r = 0.70$ - 0.87 for free and total testosterone respectively using a radioimmunoassay (RIA) technique in men and women. Johnson et al., (233) reported a significant correlation ($r = 0.83$; $p < 0.01$; n = 194) between salivary and serum free testosterone in men and women while Dabbs (112) reported significant ($p < 0.001$) correlations using a similar RIA methodology between saliva and serum free testosterone across hours ($r = 0.50$ - 0.67), days ($r = 0.64$ - 0.74) and weeks ($r = 0.74$ - 0.88) in a series of studies conducted on a large subject group of 270 males and 175 females. Similarly, other researchers (242) have reported significant correlation between sTest and plasma testosterone in men and women subjects ($r = 0.71$; $p < 0.001$) during morning and evening measurement, with significantly ($p < 0.005$) higher total and free sTest levels in the morning than the evening. Accordingly, investigators should consider diurnal variations in salivary endocrine measures when determining daily sample collection protocols. Khan-Dawood et al., (242) reported that hourly variations in salivary total and free testosterone were

remarkably similar to plasma total and free testosterone respectively, confirming the use of sTest measurement as a useful, simple, non-invasive valid and reliable method to determine endocrine status during repetitive daily testing.

Salivary cortisol levels have also demonstrated high correlation with free serum cortisol levels at rest and under exercise conditions (65, 192, 265, 323, 341, 456). In an examination of sCort and serum cortisol in response to repeated sample collection at frequent intervals under resting pre-exercise and post 10 min of treadmill running at 90 % HR_{max}, Grozansky et al., (192) reported significant correlations ($p < 0.001$; $r = 0.60$) between sCort and serum cortisol levels. The findings of Grozansky et al., (192) support the concept that salivary cortisol represents the biologically active free fraction of cortisol and the authors recommend that the assessment of sCort would be considered over serum cortisol measurement due to the physiological relevance of data associated with the biologically active form of cortisol during and post exercise. Similar significant correlations have been reported before ($r = 0.52$; $p = 0.005$) and after ($r = 0.62$; $p = 0.001$) a moderate intensity superset full body resistance exercise protocol (total 16 sets x 8 reps; 65 – 75 % 1RM; 90 – 120 s between superset sets) in healthy men (65), these data further supporting the use of salivary cortisol analysis in response to exercise.

Additional correlations have been reported between sCort and serum cortisol during sub-maximal cycle ergometry (341, 361) and maximal running (323) exercise protocols. In a study by Port (361), significant correlations ($r = 0.86$; $p < 0.001$) were observed between sCort and serum cortisol during a sub-maximal incremental cycle ergometry test however the same correlations were not observed at maximal intensities. Similarly, O'Connor et al., (341) performed serial sampling of blood and saliva on five occasions at 15 min intervals pre, during and post a 30 min cycle ergometry exercise protocol performed at 75 % of subjects VO_2 max. The results of the study (341) found significant ($p < 0.01$) correlations between sCort and serum cortisol at all five sampling periods, namely 15 min pre (r = 0.89), immediately pre ($r = 0.60$), following 15 min exercise ($r = 0.72$), at the completion of 30 min exercise ($r = 0.90$) and following 15 min recovery ($r = 0.93$) supporting the validity of sCort as a valid measure of serum cortisol in response to short-term cycling. Under maximal exercise conditions, Neary et al., (323) examined the relationship among resting cortisol levels in saliva and serum to determine the most appropriate method to monitor recovery from the physiological stress imposed by a shuttle run protocol to volitional fatigue. Neary et al., (323) reported a high correlation ($r = 0.99$) between sCort and serum cortisol at rest and under recovery conditions post-exercise suggesting salivary cortisol is a reliable indicator of serum free cortisol and a useful technique to study cortisol changes during exercise and the post-exercise recovery period.

In a comparison of T:C values obtained from hormonal assays in saliva and serum, Obminski & Stupmicki (342) reported that the salivary T:C (sT:C) is a better index in comparison to the T:C

obtained from serum on that basis that saliva levels of the hormones reflects the biologically active (free fraction) of testosterone and cortisol in the circulation (265) thereby providing an alternate and uninvasive method of endocrine analysis following exercise. Determinations of sTest, sCort and sT:C in athletes may therefore be used to assess functional endocrine status and indirectly measure the biological active fractions of steroid hormones (342) and provides substantially greater scope for the implementation of frequent endocrine monitoring interventions in athlete populations.

2.4.3 Testosterone and Cortisol Responses to Exercise

The influence of various types of acute and chronic physical exercise on the salivary and serum levels of testosterone and cortisol has been the focus of many investigations (6, 53, 103, 157, 218, 229). Resistance training (RT) is a potent stimulus for acute increases in the concentrations of circulating hormones such as testosterone and cortisol (53, 402). The majority of studies that have considered hormonal changes induced by RT sessions have reported acute increases in cortisol (102, 253, 302) total testosterone and free testosterone on men (102, 258). Such elevations in the testosterone response to RT have been attributed to plasma volume reductions, adrenergic stimulation, potential adaptations in testosterone synthesis and / or the secretary capacity of the Leydig cells while some cortisol elevations have reportedly remained elevated when corrected for plasma volume changes (258).

Heavy RT has been shown to induce acute hormone responses, which are influenced by the type of exercise, intensity, volume, rest periods and muscle mass involved during said RT exercises (5, 7, 188, 257, 459). A study by Ahtiainen et al., (5) examined the short and long term total and free testosterone and cortisol response to two separate three month hypertrophy based RT protocols over a six month duration in a crossover design in trained men. Ahtiainen et al., (5) manipulated the intensity and rest periods associated with the RT protocol (i.e. higher intensity and longer 5 min rest vs lower intensity and shorter 2 min rest) and examined the plasma total and free measures of testosterone and cortisol at 15 min intervals pre-, immediately post, and at 15 min and 30 min post RT. Interestingly, both protocols resulted in significant ($p < 0.05 – 0.001$) increases in testosterone and cortisol post-RT. No significant difference was found between RT protocols despite manipulation of intra-set recovery periods indicating that large acute hormonal responses may be evoked from a variety of RT loading and intensity schemes (5) and over longer periods of training. In general however, a trend of attenuated acute testosterone and cortisol responses were observed during the six month training period. The diminished acute endocrine response may be indicative of a decreased stress response and / or decreased hormone production and may have been a reflection of endocrine system adaptation to the flat volume loading scheme implemented or the manifestation of overtraining during the prolonged

training period. The results of Ahtiainen et al., (5) may therefore be an important consideration with respect to long term multi-disciplinary training adaptations in team sport athletes over extended seasons, such as the 26 week NRL season, where players participate in regular strength training sessions in conjunction with other training activities on a daily basis.

Metabolically demanding RT protocols that are high in total work and characterised by high volume, moderate intensity with short rest periods have been found to elicit the greatest cortisol response during strength training (200). McGuigan et al., (302) reported a significant (97 % ; $p < 0.05$) increase in sCort immediately following a high intensity RT protocol consisting of 6 x 10 reps at 75 % 1RM of squat and bench press exercise. Alternatively, no significant change in sCort was evident following a low intensity protocol of 3 x 10 - 30 % of one repetition maximum (1RM) with 2 min rest between sets in both protocols. The results of McGuigan et al., (302) found that sCort was significantly different ($p < 0.05$) immediately post-exercise between high and low intensity RT and that sCort levels were significantly ($p < 0.05$) elevated when a higher volume and higher intensity of work was performed. McGuigan et al., (302) concluded that sCort was a valid and reliable method of quantifying the endocrine response to RT and the findings are of interest in an applied monitoring setting on the basis that sCort was found to respond rapidly to exercise load. It may be that the intensity and or total volume of exercise is a key determinant of resultant endocrine responses rather than the type or order of exercise. The role of cortisol to monitor the short term recovery response to high intensity intermittent exercise that is characteristic of elite Rugby League match-play may therefore be an important consideration for sports scientists to determine training loads and exercise regimes to optimise subsequent performance.

Recently, the acute response of sTest and sCort to a variety of RT protocols have been examined (32, 33, 102). In a study incorporating four distinct RT protocols of varying volume and intensity, Beaven et al., (33) reported significant ($p < 0.05$) individual, protocol-dependent hormonal responses for up to 30 min post exercise. On four occasions, separated by at least two days, subjects performed RT protocols that consisted of the same upper and lower body exercises in the same order under different loading parameters, namely 4 x 10 - 70 %, 3 x 5 - 85 %, 5 x 15 - 55 % or 3 x 5 - 40 % of 1RM. Salivary testosterone and sCort were measured pre, post and 30 min post exercise. Pooled data (n = 23) revealed no significant ($p > 0.05$) change in sTest in response to all RT protocols, although significant ($p < 0.01$) pre- to post- exercise reductions in sCort were observed during the 3 x 5-40 %, 3 x 5-85 % and 4 x 10-70 % protocols but not for the 5 x 15-55 % RT protocol (33). Beaven et al., (33) reported large individual differences in sTest and sCort responses between subjects highlighting the fact that athletes will respond differently to RT protocols. These results (33) confirm the necessity for each athlete to be employed as his or her own control for performance and recovery monitoring purposes following training and competition.

The importance of exercise volume and intensity in relation to RT protocols has also been provided by Crewther et al., (102) in their analysis of squat workouts incorporating either a power (8 x 6 reps at 45 % 1RM; 3 min rest between sets), hypertrophy (10 x 10 reps at 75 % 1RM; 2 min rest between sets) or maximal strength (6 x 4 reps at 88 % 1RM; 4 min rest between sets) training. Salivary testosterone and sCort were measured pre and post-exercise and at 15 min intervals for up to 60 min post RT. The results of Crewther et al., (102) revealed significant ($p < 0.05$) increases in sTest and sCort following the hypertrophy protocol with little or no hormonal change in response to the power or maximal strength schemes ($p > 0.05$). Furthermore, the post-exercise sTest and sCort responses to the hypertrophy protocol was significantly ($p > 0.05$) different to the power and maximal strength protocols that displayed relatively similar hormonal profiles. Crewther et al., (102) attributed the differing endocrine response between loading schemes to variation in volume and load. These findings (102) lend support to the concept that salivary hormone analysis exhibits a more dynamic response to intense exercise than total hormone levels, increasing the scope of saliva hormonal measures to monitor the acute response to training and competition the post-competition recovery period. The volume and intensity of exercise are key considerations associated with the design of short and long term training programs and the determination of total work performed during each training session. Accordingly, an appropriate amount of total work will induce optimal anabolic to catabolic endocrine responses to facilitate adaptation and recovery in athletes such as elite Rugby League players participating in extended regular season competitions.

Further analysis of the impact of exercise intensity on endocrine responses has been provided by Jacks et al., (229) in an analysis of sCort measures following repeated cycle ergometry bouts of 1 hr duration performed at low (44.5 ± 5.5 % VO_2 max) moderate (62.3 ± 3.8 % VO_2 max) and high (76.0 ± 6.0 % VO_2 max) intensity. Salivary cortisol was measured before exercise, at 10, 20, 40 and 59 min during exercise and following 20 min of recovery. While the sCort measured at 59 min and 20 min post the high intensity cycle ergometry were significantly higher ($p = 0.004$ & $p = 0.016$ respectively) than the low and moderate intensity protocols, no significant differences in cortisol were noted between the low and moderate intensity protocols. Interestingly, exercise < 40 min in duration elicited no significant differences at any level of intensity suggesting only cycle ergometry of high intensity and long duration produces significant elevations in salivary cortisol (229). Alternatively, other researchers (341) have reported significant ($p < 0.05$) increases in serum and sCort immediately and 15 min post sub-maximal cycle ergometry performed at 75 % VO_2 max for 30 min highlighting the high level of variability that exists with regard to endocrine measurement during low, moderate and high intensity exercise.

Hoogeveen et al., (218) examined the effect of intensive (405-740 km/wk; 15.5 ± 3.5 - 26.4 ± 4.1 hr/wk) cycling training on testosterone and cortisol in endurance trained professional cyclists during cycle ergometry to exhaustion. Post-training, resting testosterone significantly decreased ($p < 0.05$), resting cortisol significantly increased ($p < 0.05$) while testosterone and cortisol both increased significantly ($p < 0.05$) immediately post-exercise. The resting levels of testosterone and cortisol and the acute response to exercise following intensive cycling training showed no correlation with performance pre or post training despite an increase in catabolic state (218). Interestingly, post-training cycle ergometry performance improved despite the presence of a catabolic endocrine profile in cyclists. The results of Hoogeveen et al., (218) are of particular interest for athletes participating in regular bouts of high intensity training and competition such as elite Rugby League players, where there may be a requirement to participate in competition under a predominantly catabolic state due to a prolonged endocrine response following previous performance and or insufficient recovery between matches.

The effect of high intensity interval exercise incorporating running and cycle ergometry on post-exercise indices of training stress and performance has been evaluated (153). Trained male distance runners completed either a running or cross-training exercise protocol three days per week over a period of six weeks (Monday 5 x 5 min at > 95 % VO_2 max; Wednesday 50-60 min at 70 % VO_2 max plus 3 x 2.5 min at > 105 % VO_2 max, and Friday 6 x 1.25 min at > 115 % VO_2 max). Total testosterone, free testosterone and cortisol were measured following a 5 km simulated race on a treadmill at week 0, 3 and 6 of the training protocol. The results of Flynn et al., (153) revealed no significant difference in testosterone measures between training groups or across time nor was there a significant difference in cortsiol at week three or six of the training protocol, however cortisol was significantly ($p < 0.05$) greater in both the running and cross-training groups in comparison to controls. The results of Flynn et al., (153) found that similar endocrine responses to interval based training may be elicited regardless of the mode of exercise, this finding may have important implications for the inclusion of variation in the mode of training for athletes with similar training backgrounds.

The influence of multiple training methods on testosterone, cortisol and T:C have been examined before and after five weeks of speed, speed endurance, endurance, plyometrics and strength training in competitive male sprinters and jumpers (359). Subjects completed a short (3 x 4 x 60 m at 91 - 95 % of personal best with 2 - 3 min rest between sets) and long interval run session (n x 20 s treadmill sprints with 100 s between runs to exhaustion) on consecutive days before and after the five week training block to determine fasting testosterone, cortisol and T:C. No significant changes were found in hormonal status immediately following the short repeated sprint protocol however the series of repeated 20 sec sprints to exhaustion elicited significant increases in testosterone ($p = 0.002$; 30.4 %), cortisol ($p = 0.006$; 12.0 %) and T:C ratio ($p = 0.047$; 21.0 %) (359). The results of Pitkanen et al.,

(359) indicate that subjects were able to maintain an anabolic endocrine profile despite participating in relatively high volume and high intensity training throughout the five week training period. While the influence of multiple training stimuli and the consequences of muscle damage associated with collisions during match play over prolonged periods > 5 weeks remain unclear, however the findings of Pitkanen et al., (359) suggest players may be able to maintain a positive anabolic state in response to training, thereby optimising recovery to facilitate performance.

Additional studies (145, 444) have examined the endocrine response to prolonged endurance exercise. Tremblay et al., (444) examined hormone concentrations in endurance trained male subjects following prolonged treadmill running exercise at a constant intensity of 50 - 55 % VO_2 max for either 40, 80 and 120 min. Total and free testosterone, cortisol and T:C were measured before each running session and then 1, 2, 3, and 4 hr after the start of each run. Total testosterone was found to be significantly ($p < 0.05$) greater during the 80 min run compared to the 40 min run. Total and free testosterone then underwent a steady decline for the remaining 3 hr of sample collection suggesting testosterone responds to increased exercise duration in a dose response fashion. Cortisol showed a steady decline across all time during running sessions of 40 and 80 min duration. The T:C was significantly greater at rest and following the 40 min run ($p < 0.05$) in comparison to 80 and 120 min running bouts (444). The results of Tremblay et al., (444) reveal that when the exercise intensity is maintained, the duration of exercise may yield an independent, dose-response influence on the endocrine response to endurance exercise in trained males. In this case, a relatively high volume of running (> 80 min) was required to elicit an endocrine response when performed at low exercise intensity (55 % VO_2 max).

Others (145) have examined the testosterone and cortisol response to endurance exercise have identified significant ($p < 0.01$) increases in total testosterone, free testosterone and cortisol following 45 min treadmill running at 70 % VO_2 max, further establishing the considerable influence of intensity and duration on the endocrine response to endurance exercise throughout a prolonged competition period in team sport athletes such as elite Rugby League players participating in the NRL. Elite Rugby League match-play is comprised of 80 min of repeated bouts of intermittent high intensity and low intensity running activity over a total duration of 80 min. Furthermore, daily training practices in elite Rugby League commonly consist of 60 – 120 min of mixed method low, moderate and high intensity running activities. The results of Tremblay et al., (444) therefore may be an important consideration for the prescription of training volume, intensity and total training load during the course of a regular season period of elite Rugby League competition.

To further examine the influence on prolonged heavy physical stress on anabolic and catabolic endocrine concentrations, Maestu et al., (291) investigated the hormonal response at rest and during a maximal 2000 m rowing ergometer test in trained male rowers before and after 3 wk of overload

training followed by a 2 wk taper period. Total and free testosterone, cortisol and T:C were determined pre-, immediately post and 30 min following each of the three maximal rowing performance tests. No change in resting total testosterone and cortisol values was found between the three maximal rowing tests. Resting free testosterone and free T:C were significantly reduced ($p < 0.05$) at the completion of 3 wks of overload training but returned to baseline concentrations following 2 wks of training volume reduction. Total testosterone and cortisol were significantly ($p < 0.05$) elevated while free testosterone was significantly reduced ($p < 0.05$) immediately following maximal rowing performance test on all three occasions. At the completion of 3 wk of overload training and following a 2 wk taper, significant ($p < 0.05$) increases in cortisol and reductions in testosterone were evident in association with a reduced ($p < 0.05$) T:C 30 min post testing (291). Persistent increases in cortisol, reduced testosterone and a suppressed T:C profile may indicate a decreased adaptive capacity of rowers to tolerate three consecutive wk of high volume overload training. The results of Maestu et al., (291) indicate that testosterone and cortisol are sensitive to overload training doses and therefore may have important implications for training program design and the manipulation of periods of planned overload during multiple training phase periodisation models during the course of a competitive season period, such as that commonly incorporated into NRL team training models.

Regarding the endocrine response to sport specific training, Moore & Fry (316) investigated the performance and hormonal responses to a 15 week off-season American Football training period in college aged males. Phase 1 of the training period consisted of moderate volume and moderate intensity RT only (5 x 10-76 % 1RM x 4 sessions per wk) followed by a 5 wk of concurrent moderate volume high intensity RT and high-volume general conditioning drills during Phase 2 (5 x 10 reps at 92.5 % 1RM x 4 sessions per wk) while Phase 3 incorporated 4 wk of spring football practice drills and scrimmage sessions. Testosterone, cortisol and the T:C were assessed prior to the commencement of Phase 1 and at the completion of Phase 1, 2 and 3 of American Football training. Testosterone levels were significantly ($p < 0.05$) reduced during Phase 2 of training followed by a return to baseline at the completion of Phase 3 while cortisol and the T:C did not change during any phase of the study. Although testosterone decreased during the period of high volume conditioning and high intensity RT completed during phase 2 of the study, no significant change in the T:C was evident, suggesting the endocrine profile of subjects was predominantly anabolic and indicative of adequate recovery following training loads (316). Moore & Fry (316) noted the importance of individual T:C ratio monitoring to determine players adaptation to training in comparison to group trends and provides further support for the ability of contact sport athletes, such as American Football players and elite Rugby League players to tolerate multiple training stimuli on a daily basis over an extended period.

Additional evidence of the influence of multiple training stimuli in contact sport athletes during a specific preparation period has been reported in sub-elite Rugby League players (97). Coutts et al.,

(97) examined testosterone, cortisol and the T:C ratio pre- and post 6 wk of progressive overload training that included 5-7 session per wk of field based specific Rugby League training, aerobic endurance development, RT, speed and agility training and following a 7 day taper period at the completion of the training block. The results of Coutts et al., (97) revealed a non-significant tendency for a reduction in testosterone and an increase in cortisol following the 6 wk multi-discipline overload training or taper period. There was however a significant ($p < 0.05$) reduction in the T:C ratio at the completion of 6 wks training and remained reduced following taper ($p < 0.05$) indicating players were in a catabolic state and remained so despite a 7 day recovery period. Coutts et al., (97) suggested that the reduced T:C ratio was due to inadequate recovery during the 6 wk training period, however the researchers failed to consider the influence of non-training factors such as labour intensive occupations, non-individualised training loads and self directed post-training recovery practices of participants that are likely to have contributed to anabolic:catabolic endocrine profile of semi-professional Rugby League players. The findings of Coutts et al., (97) should therefore be viewed with caution for comparison with anticipated anabolic:catabolic endocrine response of elite Rugby League players. These results (97) do however support the use of T:C ratio as a worthwhile measure to monitor adaptation and recovery, and potentially assist with the identification of fatigue in response to Rugby League specific training activities.

2.4.4 Testosterone and Cortisol Response to Sports Performance

The effects of physical exercise on testosterone and cortisol levels have been widely documented in laboratory and field based research (5, 33, 102, 218), however competitive sports performance may also elicit psychophysiological endocrine responses in athletes that are influenced by additional variables such as anticipation and anxiety associated with the outcome and emotion. Although an anticipatory cortisol response prior to physical stress during exercise has long been recognised, recently it has been reported that competition elicits a pre-exercise endocrine response of elevated cortisol and testosterone (52). There is evidence of elevated cortisol and reduced testosterone in response to psychologically stressful situations (214). Alternatively, it has also been suggested that a parallel increase in testosterone and cortisol is associated with a pre-exercise preparatory response that is specific to competitive settings (52). Consequently, there has been considerable interest in the endocrine response, and in particular the response of testosterone and cortisol pre, during and following competitive athletic activities (147, 149, 203, 264, 285, 353).

Although the results for testosterone in response to competition are varied and may be influenced by prior competitive experience, motivation and perception of opponent skill levels (247), the trend of

increased pre-match cortisol is thought to reflect a psychophysiological mechanism influenced in part by cognitive anticipation and anxiety used by athletes as a pre-competitive arousal and coping mechanism used to manage pre-competition stress (214). Moderate elevations in cortisol have been linked to improved athletic performance via positive influence on cognitive function in the form of facilitated memory and learning, regulation of homeostatic function (247). Extreme increases in cortisol however have been associated with poor athletic performance via negative influences on testosterone production and cognition (52, 109, 247).

The sCort, sTest and sT:C of elite male weight-lifters have been investigated by Passelergue et al., (354) during an official weight-lifting tournament and simulated weight-lifting competitions. Saliva samples were collected for analysis on three occasions during each session, namely at weigh-in and then after three attempts at the snatch and clean-and-jerk lifts. The results of Passelergue et al., (354) revealed a significant change in sTest throughout competition and simulation, or between tests. Conversely, sCort was significantly ($p < 0.05$) higher while the sT:C was significantly lower ($p < 0.001 – p < 0.05$) during competition in comparison to simulation, highlighting the influence of performance anxiety and the potential influence of an increased catecholamine response on sCort in elite weight-lifters (354).

The link between athletic performance and endocrine responses during competition has been examined in novice and experienced rowers (247). In an examination of sTest and sCort pre-, 20 min post and 40 min post competitive rowing ergometry over 2000 m, an anticipatory decrease in sTest ($p < 0.05$) was found in both groups pre-competition followed by an increase ($p < 0.05$) 20 min post race and subsequent drop in sTest ($p < 0.05$) in novice rowers while no change was elicited in experienced rowers in response to competition. Interestingly, the degree of elevation in sTest 20 min post-race was associated with superior performance in experienced rowers, however higher sTest in novices 20 min post-race was related to poor rowing performance. Conversely, sCort was elevated pre-competition with additional and significant ($p < 0.05$) increase at 20 min post race in both groups. When measured 40 min post race, sCort remained significantly ($p < 0.05$) elevated in comparison to pre-race levels in experienced rowers while sCort returned to pre-race levels in novice rowers. Kivlighan et al., (247) concluded that prolonged increases in sCort post-race may be characteristic of experienced athletes tendency to self analyse their performance resulting in a prolonged stress response and may be an important consideration for elite Rugby League players where livelihoods and future selection is determined on a match-by-match basis.

Additional research (448) involving elite rowers has examined the anabolic-catabolic hormone response to an extended period of intensive training in conjunction with participation in repeated competition over a period of 7 wk. Testosterone, cortisol and the T:C ratio was determined on a

weekly basis for the duration of the study. Weekly competition commencing in week 2 of the study followed by 1 wk of reduced training and a return to intense training and competition for the remainder of the study period (448). Despite a demanding training and competitive schedule, no significant changes in cortisol could be discerned for the duration of the study, however a pattern of progressively reduced testosterone (significantly decreased from week 5 – 7; $p < 0.001 – 0.05$) was elicited in conjunction with significantly lowered T:C ratio in weeks 6 and 7 (448). Most notably, the response of testosterone corresponded to the intensity of physical strain, decreasing after intense physical exercise and remaining unchanged or slightly elevated during periods of reduced intensity. Similarly, the T:C ratio continuously decreased after intense training or competition, indicating an increase in catabolic activity, insufficient recovery and an inability of athletes to cope with training and competitive load during consecutive weeks of competition, such as that experienced by elite Rugby League players during the 26 wk NRL season.

The concept of reduced T:C as a marker of incomplete recovery from intensive training or competition that is not necessarily related to overstrain or overtraining is supported by other researchers (25, 26, 454). In particular, Banfi et al., (26) reported a pattern of sporadic performance and significant ($p < 0.05$) reductions in T:C following periods of intensive training and throughout the course of an eight month in-season period of training and competition in elite speed skaters. A similar pattern of suppressed T:C in response to periods of heavy training with corresponding decreases in testosterone and elevated cortisol have been reported during an extended nine month training period preceding Olympic Games participation in elite rowers (454). The results of Banfi et al., (26) and other researchers (454) indicate an imbalance between training load, recovery time and performance in elite athletes and corroborates the inclusion of T:C as a reliable marker of athlete adaptation and recovery during prolonged periods of training and competition, such as that experienced by players in the NRL.

Regarding non-contact team sport participation and the endocrine response to competitive match-play, Lupo et al., (285) investigated the endocrine response of semi-professional players to a single soccer match. Lupo et al., (285) examined plasma testosterone and cortisol pre-match, at half time, post-match and following 45 min and 90 min of recovery post-match and revealed a tendency of increased testosterone at half time followed by significant reductions ($p < 0.02 – 0.05$) at the completion of match-play and for the duration of the 90 min recovery period. Conversely, soccer match-play resulted in significantly elevated plasma cortsiol at half time ($p < 0.001$), post-match ($p < 0.005$) and following 45 min recovery ($p < 0.01$) with a return to baseline within 90 min post-match. Lupo et al., (285) concluded that competitive soccer match-play elicited simultaneous activation of anabolic and catabolic hormones, culminating in a predominant catabolic endocrine profile immediately post-match. The tendency for cortisol to return to baseline within 90 min of match-play however is indicative of a positive shift in T:C ratio to an anabolic endocrine profile and an initiation of recovery post-match.

Further analysis of the endocrine response to a single match and season long periods of competitive soccer have revealed similar results in college (135, 203, 254), semi-professional (69) and professional (147, 148) players. In a single match analysis (n = 21) of intercollegiate soccer (135), sTest and sCort were examined pre-match and 15 min after match completion. The results of Edwards et al., (135) found post-match increases in sTest in comparison to pre-match, however the improvement did not reach statistical significance. However when the sTest for a single player (the goalkeeper) was removed from data analysis, post-match increases in sTest did reach statistical significance ($p < 0.03$). Post-match analysis of sCort from all players however was significantly ($p < 0.01$) higher than pre-match and is consistent with expected outcomes associated with stress hormone responses to physical activity and competition (135). The parallel increases in sTest and sCort following intercollegiate soccer match-play highlight the level of individual variability associated with physical activity and competition and raise the question of a single match analysis as a reliable reflection of soccer match-play given the highly dynamic nature of each player's performance in each game they play (121, 191). Accordingly, the analysis of endocrine responses to multiple matches may provide a more accurate indication of team sport match-play.

A single-match analysis of soccer has also been used for comparison with the sCort response to training in college athletes (203). Haneishi et al., (203) examined sCort response in starters (n = 10) and non-starters (n = 8) 30 min pre- and 10 min post a regular season match and a typical training session performed at an undisclosed time in relation to match-play participation. When compared with non-starters, starters exhibited significantly ($p < 0.05$) higher [sCort] than non-starters at all sample times during match-play and training. The key finding of the study (203) revealed an acute increase in [sCort] in both groups ($p < 0.05$) that was significantly ($p < 0.05$) greater in starters than non-starters. Of particular note was a 250% increase in [sCort] in starters during competition in comparison to training levels, supporting the long established intensity dependent nature of sCort in response to competitive physical exercise. The research conducted by Haneishi et al., (203) also identified an absence of elevated sCort pre-match in comparison to pre-training levels, indicating there was no anticipatory sCort response to competition. The lack of anticipatory rise in [sCort] is in contrast to the findings of other researchers (16, 353) however the considerable increase in sCort found following soccer match-play confirms the influence of competition and training load on sCort and supports the use of sCort to monitor the demands of competition in team sport athletes.

To further increase our understanding of the acute and chronic endocrine responses to team sport competition, several studies (69, 147, 148, 254) have monitored changes in anabolic and catabolic hormones over extended in-season competition periods. In an analysis of an 11 wk, 19 match regular season period of collegiate soccer (254), plasma testosterone, saliva and the T:C ratio of starters (n =

11) and non-starters (n = 14) was assessed 1 wk before the first competitive match, then during wk 3, 7, 8, 9 in-season and 1 wk after the final regular season match. Data revealed that both starters and non-starters commenced the season with low testosterone and elevated cortisol levels that culminated in a pre-season catabolic hormonal profile. Throughout the course of the season however, a pattern of progressive increases in testosterone were recorded with a significant ($p < 0.05$) increase in testosterone observed for both groups 1 wk following the final match of the season. Differences between groups were only recorded during wk 3 of the season with non-starters displaying significantly ($p < 0.05$) higher testosterone than starters. One week prior to the commencement of the season, cortisol was significantly ($p < 0.05$) higher in non-starters than starters. There were no significant changes in cortisol concentrations during the season, with the exception of a late-season measure in wk 8 of the competition during which starters experienced a significant ($p < 0.05$) increase in cortisol in comparison to non-starters. The T:C ratio also displayed no significant changes during the season but increased ($p < 0.05$) 1 week following the completion of match-play in non-starters only. The results of Kraemer et al., (254) suggest the endocrine response of soccer players during a full season competition period is independent of match-play. The pre-season response of anabolic and catabolic endocrine response may be influenced by training volumes and stress associated with performance expectations and stress regarding team selection. Further, during the regular season period, athlete preparation variables such as training and recovery may have a greater influence on endocrine measures than actual match-play participation, particularly during a season with multiple matches per week allowing little time for high volume or high intensity training. The findings of Kraemer et al., (254) provide further support of the use of testosterone and cortisol to monitor team sport athletes throughout competitive seasons of weekly match-play.

In professional soccer players (147, 148), the anabolic:catabolic endocrine response to an extended season of training and competition has shown further variation to the results of other researchers that have examined college (254) and semi-professional (69) players. In an examination of a 9 month (mth) period of training and competition, the response of sTest and sCort were determined on four occasions, namely at the commencement of training for the upcoming season and at intervals of 7, 12 and 16 wk of training and competition. Despite considerable manipulation of training load variables and match-play participation for the duration of the study, no change in sCort was observed at any stage of the season. Conversely, sTest decreased significantly ($p < 0.01$) during the course of the 9 mth study period. An interesting finding of Filaire et al., (148) revealed that despite significant ($p < 0.05$; > 30 %) reductions in the sT:C to levels traditionally associated with overtraining (4), no decrement in match-play performance was evident in professional soccer players despite a predominant state of catabolism. The findings of Filaire et al., (148) regarding suppressed T:C ratio and athletic performance are consistent with other researchers (448, 454) and demonstrate that a reduction in T:C ratio does not automatically lead to a decrease in performance or overtraining.

Rather, decreased T:C ratio may reflect a reduction in the ability of players to tolerate training and competitive loads due to the extended nature of professional competition schedules such as that experienced by players in the NRL.

Rugby League is a form of high-intensity, intermittent exercise of 80 min duration involving frequent collisions with opponents and is influenced by psychological factors associated with anxiety and perceived stress, and particularly so for elite players participating in match-play in front of 10,000 – 60,000 spectators and watched by millions of people world-wide on television and other electronic media outlets. Although an analysis for the endocrine response to a variety of individual and team sports provides some insight to the mechanisms associated with athlete adaptation to the demands of training and competition, considerable variation with regard to intensity, volume, skill level and the absence of repeated contact during performance raises questions regarding comparisons to elite Rugby League match-play. No studies have considered the acute or chronic anabolic and catabolic endocrine response Rugby League match-play, therefore an analysis of endocrine responses during contact sports such as American Football, Australian Rules Football, and Rugby Union may provide insight into the influence of collision and repeated blunt force trauma that is characteristic of elite Rugby League competition.

2.4.5 Endocrine and Neuromuscular Responses to Contact Sport Match-Play

The combative nature of Rugby League match-play with repeated high velocity blunt force trauma characteristic of American Football (213, 259) and Rugby Union (111, 401) interspersed with running volumes comparable with soccer (27, 61) and Australian Rules Football (91, 116) provides a unique model in which to examine the time course of endocrine and neuromuscular responses to competition that has not been reported previously. Accordingly, a review of combative and repeated collision sports may provide further insight into the response of athletes to the physical demands of match-play and the pattern of recovery in preparation for subsequent performance. The evolution of elite Rugby League match-play has seen considerable focus on the development of grappling and wrestling related skills to assist a player to control an opponent during ruck related activity that is part of each tackle. Further, it has been suggested by some researchers (163) that success in Rugby League is dependent in part on the ability to tolerate physical collisions and the ability to ‘win’ the tackle contest. On average, players will take part in a match-specific activity in the form of completing a tackle, carrying the ball or playing the ball approximately every min of match-play (396), therefore consideration of the physiological demands of the wrestle related component of Rugby League match-play is warranted.

Studies that have considered the endocrine response to competitive judo (149, 379, 380) and wrestling (255, 353) have identified a high level of individual variation among athletes in response to combative sport participation. Filaire et al., (149) examined the endocrine response of experienced Judo athletes (n = 12) to competition. Salivary hormone levels of sTest and sCort were measured upon awakening on the day of competition and then five min before the first and five min following the last fight of each athlete at regional and inter-regional level championship tournaments. The results of Filaire et al., (149) revealed no statistically significant change in sTest at any stage during either tournament. The sCort was significantly greater before ($p < 0.001$) and after ($p < 0.001$) inter-regional than regional competition that in turn was greater ($p < 0.05$) than baseline resting values and implies a psychological component of increase sCort in response to higher levels of competition. Similarly, other researchers (379) have reported pre-competition increases ($p < 0.02$) in sCort during regional level judo competition (n = 17) with no change in sTest. Salvador et al., (379) however note that high inter-individual endocrine variability and the influence of motivation and positive mood may have contributed to the lack of sTest response in Judo athletes. Variable fight schedule and specific individual bout considerations in addition to lengthy time frames between sample collection (several hours) evident in the work of Salvador et al., (379) may limit comparison between judo competition and Rugby League match-play.

To further increase our understanding of the contribution of the endocrine and neuromuscular response to combative sport competition, an analysis of wrestling specific physical contact may be of value due to the common application of wrestling activities in elite Rugby League training and the characteristics of the tackle during match-play. Accordingly, Kraemer et al., (255) examined serum testosterone and cortisol levels in conjunction with VJ performed on a force platform of collegiate wrestlers (n = 12) during a simulated 2-day tournament. During the study (255), subjects participated in five wrestling matches (Day 1: 10am, 2pm, 6pm; Day 2: 10am 7pm) with testing completed immediately pre and post each match. In contrast to the endocrine responses reported during Judo competition (149, 379), significant increases ($p < 0.05$) in testosterone from pre- to post-match were seen across all matches during the five match tournament. Pre-match testosterone exhibited a chronic and progressive decrease ($p < 0.05$) to levels well below baseline by the end of the second day of the tournament. Alternatively, cortisol measures were significantly ($p < 0.05$) elevated following all matches with the exception of match three at the completion of Day 1 of the competition (255). Pre-match cortisol was significantly ($p < 0.05$) lower than baseline and each preceding match on both days of the tournament while significant ($p < 0.05$) reductions in VJ power were identified immediately following the remainder of matches on day 1 and prior to the commencement of the first match on day 2. Kraemer et al., (255) reported that the decrease in testosterone throughout the tournament was indicative of a shut down of the hypothalamic-pituitary-gonadal axis in conjunction with elevated catabolic processes and a continuous reduction in anabolic status to produce decrement in muscle force and power

characteristics. The findings of Kraemer et al., (255) therefore support the use of anabolic and catabolic endocrine measures to reflect a cumulative effect of performance based stress with repeated exposure to wrestling competition and a resultant increase in neuromuscular fatigue that may be experienced by elite Rugby League players during the course of repetitive match-play.

In an additional study of endocrine variations during a 2-day wrestling competition and during the post-competitive recovery period, Passelergue & Lac (353) compared baseline sTest, sCort and sT:C ratio measures to pre- and post-wrestling match (n = 15) participation and at 24 hr intervals for a period of eight days post competition. While wrestling competition did not induce any statistically significant changes in sTest during either day of competition, significant ($p < 0.05$) increases were observed in sTest on day 1 of the recovery period and remained elevated for the duration of the eight day testing period. In contrast, sCort was found to be significantly ($p < 0.05$) elevated prior to the commencement of the competition with subsequent acute and significant ($p < 0.05$) increases identified at all measurement intervals for the duration of the two day tournament in comparison to baseline measures. Following the completion of competition however, sCort returned to baseline within 24 hr of match-participation and remained unchanged during recovery. In response to unchanged sTest and elevated sCort during competition the sT:C was significantly ($p < 0.05$) reduced at all testing intervals over the 2-day tournament. However, the return of sCort to baseline within 24 hr of the final match, and elevations in sTest during recovery elicited a paradoxical and significant ($p < 0.05$) increase in sT:C from day 1 to day 4 of the post-tournament recovery period (353). Passelergue & Lac (353) concluded that the sT:C is a worthwhile index of anabolic-catabolic endocrine status and recovery and further supports the use of salivary T:C as a marker of athlete status following contact sport participation.

Consideration of the endocrine response to the sports of judo and wrestling may provide some insight into the combative component of the tackle in Rugby League match-play, however there is considerable difference between the metabolic requirements wrestling tournament participation and elite Rugby League competition. Commonly, the performance characteristics of American Football, ARF and Rugby Union match-play are compared to Rugby League on the basis of the intermittent nature of high intensity exercise and repeated collision are characteristic of the four main professional contact sport football codes. To this effect, several studies (215, 216, 259) have examined the biochemical and endocrine responses of collegiate American Football players to match-play and the time course for a return to pre-match biochemical and endocrine measures during the post-match recovery period.

An analysis of American Football match-play, Kraemer et al., (259) examined the serum testosterone, cortisol and T:C ratio in college players (n = 28) 24 hr pre, 18-20 hr post and 40-44 hr following

match-play. No significant change in testosterone was observed over the time frame analysed in a finding that is consistent with that of Hoffman et al., (216). Unfortunately, no measure of the immediate post-match cortisol response was determined to establish an acute response to competition, however the results of Kraemer et al., (259) did report that no change in cortisol or T:C ratio was evident 18-20 hr post match. Following 40-44 hr recovery post-match, cortisol was found to be significantly reduced ($p < 0.05$) in comparison to earlier measures producing a concomitant increase in the T:C ratio indicting a stable anabolic hormonal profile and full recovery of players within 2 days of match-play (259).

An additional examination of the endocrine response of college American Football players (n = 21) during a 10 wk pre-season training camp followed by an 11 wk regular season period (215) have revealed no significant changes in serum testosterone, cortisol and the T:C ratio that are consistent with the findings of other researchers (216, 259). A significant ($p < 0.05$) reduction in cortisol in conjunction with an increased T:C ratio ($p < 0.05$) was observed at the completion of a 10 wk training camp however no other significant changes were evident in any endocrine measure through-out the remainder of the season, suggesting hormonal homeostasis was maintained and adequate recovery was achieved between matches throughout the season. Although there would appear to be a natural tendency for comparison between the physiological requirements of American Football and elite Rugby League match-play, substantially lower work:rest ratios and an increased frequency of blunt force trauma during collisions between players are evident during elite Rugby League match-play. The considerably greater metabolic demand of elite Rugby League match-play in comparison to American Football competition raises questions regarding the appropriateness of such comparisons.

In a study (216) that investigated neuromuscular, biochemical and endocrine responses of starters (n= 11) and non-starters (n = 10) during the final inter-collegiate American Football match of a season, serum testosterone and cortisol were measured on the morning of the match (pre) and then 15 min after the completion of match-play. To determine the neuromuscular response to match-play, PF, PP and PRFD were measured during a single maximal SJ and CMJ performed on a force plate 10 min before kick off and at the completion of each quarter of the match. The results of Hoffman et al., (216) revealed testosterone and cortisol were not altered by American Football match-play in both groups however cortisol was determined to be significantly higher in starters than non-starters ($p < 0.05$) post-match. Hoffman et al., (216) noted a tendency for cortisol to be elevated on the morning of the match in starters, indicating arousal in preparation for competition. As may have been expected, PF and PP were significantly ($p < 0.05$) influenced by American Football competition with reductions in PF and PP during both the SJ and CMJ in both groups following the first quarter of the match. At half-time, PF and PP during the SJ and PP during the CMJ remained significantly reduced in comparison to pre-match levels while reductions in PF and PP remaining evident in non-starters but not starters for the

remainder of the third quarter. Hoffman et al., (216) also revealed two findings of particular interest, namely a general but not significant trend of reduced PRFD was apparent in both groups during the first three quarters of the match, and a return of both PF and PP to pre-match levels by the end of the fourth quarter of the match in both starters and non-starters. The results of Hoffman et al., (216) indicate that concentric fatigue may occur rapidly during American Football match-play and that substitute players may need to participate in additional and consistent physical activity on the sideline to maintain force and power outputs during the course of the match. Further, it would appear that reduced running volumes and extended rest periods between competitive efforts during American Football provide adequate recovery to facilitate hormonal homeostasis and may contribute to the maintenance of PF, PP and PRFD post-match.

Recently, the acute and short-term post-match response of sCort, sTest and sT:C in conjunction with single and repeated CMJ have been investigated following ARF match-play to identify useful methods for ongoing player monitoring (86). In a single match analysis protocol, subjects (n = 22) performed single and repeated CMJ on a commercially available force plate and provided saliva samples 48 hr pre-match, immediately pre and post-match and at 24 hr intervals for a period of 120 hr post-match. The results of Cormack et al., (86) revealed an unclear pattern of response for sTest at all comparison points with moderate reductions identified immediately (- 21.8 %) and 24 hr (- 26.5 %) post-match. Alternatively, sCort and the sT:C showed the greatest change among endocrine variables however only sCort demonstrated a substantial change from 48 hr pre to immediately pre-match, indicating an anticipatory response similar to that reported previously (16). Substantial increases in sCort immediately (+ 34.2 %) and 24 hr (+ 41.8 %) post-match were followed by a return to baseline within 72 hr post-match. Post-competition, a reduction in sT:C was elicited immediately (- 36.0 %) and 24 hr (- 43.7 %) post-match, reflecting a catabolic state in response to ARF match-play. An absence of measures at 48 hr post-match and unclear or trivial changes in all measures for the remainder of the five day recovery period however makes it difficult to draw conclusions regarding the anabolic-catabolic status beyond 24 hr of recovery following ARF match-play.

In addition to the endocrine response to ARF match-play simultaneous measures of neuromuscular performance revealed substantial decrement in pre- to post-match single CMJ flight time:contraction time ratio (86). Concurrently, substantial reductions were reported in single CMJ AP, relative AP and relative average force immediately post and 24 hr post match-play (- 1.5 % to – 9.4 %) and may indicate incomplete recovery of the neuromuscular system. The mean force decrements were found to be resolved within 3 days post-match, therefore Cormack et al (86) reported that the use of force and power variables may be useful to monitor neuromuscular fatigue on the basis that prolonged reductions in relative mean force > 72 hr post-match may indicate delayed recovery in ARF players. Accordingly, the work of Cormack et al., (86) provides important information regarding elite player

adaptation to match-play and supports the use of PF and PP measures in conjunction with sTest and sCort to monitor contact sport participation and recovery.

Several studies (110, 137, 138) have examined the acute and short-term post-match endocrine and neuromuscular responses to Rugby Union match-play. Elloumi et al., (137) examined the behaviour of sTest, sCort and the T:C ratio of international level Rugby players (n = 20) during a single match and throughout the post-match recovery period. Subjects provided multiple saliva samples at the same time during each sampling session to avoid diurnal variation in endocrine measures. Baseline samples were collected at 8am, 4pm and 8pm on a rest day followed by four samples on the day of the match (8am, 4pm, 6pm and 8pm) and on twelve occasions (8am and 8pm) for a period of 6 days post-match. Match-play was completed at approximately 4 pm on the day of competition. Elloumi et al., (137) reported that Rugby Union match-play induced a significant (- 16 % ; $p < 0.05$) decrease in sTest, followed by an increase in sTest ($p < 0.01$ - 0.05) that remained evident for 72 hr post match and a return to baseline following four days of recovery. In contrast, pre-match sCort was significantly elevated ($p < 0.001$) in comparison to baseline measures, indicating cognitive anticipation and anxiety. During the match sCort increased sharply (+ 148 %; $p < 0.001$) followed by a return to baseline within 4 hrs of match-play. During the six day recovery period, sCort was reduced ($p < 0.05$) to produce an elevated T:C ratio ($p < 0.05$) that remained elevated until the 5th day post-match. Elloumi et al., (137) concluded that a high T:C ratio post-match is required to restore endocrine homeostasis following substantial psychological and physical strain during international level Rugby Union match-play. Subsequently, Elloumi et al., (137) recommended that a minimum recovery period of 7 days is required to overcome the demands of Rugby Union match-play to enable subsequent performance to be unaffected.

Additional work by Elloumi et al., (138) examined sCort and sTest values during the week following international level Rugby Union match-play and found acute increases in sCort ($p < 0.05$) with concurrent reductions in sTest immediately post-match. During the post-match recovery phase, sCort was reduced ($p < 0.05$) during the first 4 days in conjunction with a corresponding rise in sTest during the same time frame indicating that a minimum of 5 days of modified training during recovery is required to establish a return of endocrine homeostasis and player recovery. The results of Elloumi et al., (138) collaborate the findings of other research (137) that has examined the acute endocrine response of elite Rugby Union players to match-play and the time course for a return to baseline levels post-match.

Recently, analysis of the time-course of changes in endocrine markers following a single-match of international level Rugby Union (n = 10) has provided further evidence of a prolonged recovery phase post-match (110). Cunniffe et al., (110) measured testosterone, cortisol and the T:C ratio several days

pre-match, on the morning of the match, within 15 min of match completion and again on the following 2 morning (14 hr and 38 hr) post-match. Consistent with other researchers (137) that have examined the endocrine response to Rugby Union match-play, testosterone was significantly reduced (- 43 %; $p < 0.05$) immediately post-match followed by a return to baseline within 14 hr post-match. Compared to resting levels, cortisol was decreased on the morning of the match ($p < 0.05$) before increasing significantly (> 40 %; $p < 0.05$) immediately post-match. Cortisol then decreased throughout the recovery period, returning to baseline within 14 hr while the concurrent T:C ratio was significantly ($p < 0.05$) decreased immediately post-match before rising steadily throughout the recovery period resulting in T:C values following 38 hr recovery that were significantly ($p < 0.05$) higher than baseline measures. A review of recent studies (110, 137) that have investigated the endocrine response to elite Rugby Union match-play reveal a consistent pattern of reduced T:C ratio immediately post-match that remains suppressed for 14-24 hr following competition followed by a gradual increase in T:C ratio that remains elevated for up to 6 days following match-participation. This pattern of the anabolic-catabolic endocrine response to Rugby Union match-play is of particular interest for other contact sports such as elite Rugby League match-play in the NRL that consists of a varied match-schedule with recovery periods of 4-10 days between matches.

There are limited data examining the acute or short-term changes in endocrine or neuromuscular performance measures in response to elite Rugby League match-play. In an attempt to evaluate the influence of the number of days between matches on hormonal and neuromuscular responses in professional Rugby League players (n = 12), Coutts et al., (90) investigated changes in CMJ force and power characteristics with sCort and sTest during 5, 7 and 9 day periods between matches in the NRL. In an unorthodox sample collection protocol, sCort and sTest were examined 4 hr pre-match and then at intervals of 1, 2, and 4 days post-match with subsequent testing on days 6, 7, 8 or 9 post-match depending on the number of days between matches. No measurement of the acute response of endocrine or neuromuscular responses to Rugby League match-play were provided by Coutts and colleagues (90). Remarkably, no change in sTest or sCort was reported in response to elite Rugby League match-play, while all CMJ variables returned to baseline within 4 days post-match indicating that minimum of 4 days post-match is required to facilitate recovery following elite Rugby League match-play.

Although the endocrine and neuromuscular responses to contact sport match-play have been examined as relatively separate entities, several studies (12, 68, 104, 254, 354) have reported a direct influence of endocrine responses on neuromuscular performance. Crewther et al., (104) examined the relationship between a range of neuromuscular performance measures including squat jump (SJ), bench throw (BT) and sprint performance and the sTest, sCort and the T:C ratio of elite Rugby Union players (n = 34) prior to the commencement of a season of Super 14 competition. The results of Crewther et al., (104)

revealed significant correlations between SJ power and sCort (r = 0.41, $p < 0.05$) and T:C ratio (r = -0.39, $p < 0.05$). For the BT, significant correlations were demonstrated between the T:C ratio and PP (r = 0.41, $p < 0.05$) while sTest and T:C were significantly correlated with 10 m and 20 m speed measures (r = -0.48 to r = -0.56, all $p < 0.05$). The findings of Crewther et al., (104) endorse the practice combining methods to determine neuromuscular fatigue via functional exercise that evokes the SSC and markers of anabolic:catabolic endocrine status to examine the demands of training loads in elite Rugby Union players. Quantification of the time course associated with the recovery of functional measures of neuromuscular fatigue and anabolic:catabolic endocrine markers following elite Rugby League match-play represents a progression of the work of Crewther et al., (104) and is highly relevant for sports scientists to monitoring recovery and determine training loads to optimise subsequent performance.

Additional studies (68, 254, 354) have reported the existence of direct relationships between neuromuscular performance and endocrine measures in athletic populations. To this effect, Cardinale & Stone (68) reported significant positive relationships between testosterone levels and CMJ (r = 0.61, $p <$ 0.001, n = 70) in elite male and female athletes from a variety of sporting backgrounds. Further, Passelergue & Lac (354) reported a significant relationship ($p < 0.01 – 0.05$) between sCort and superior weightlifting performance (n = 13) and suggested sCort should be considered an index of performance, while Kraemer et al., (254) found significant correlations between cortisol and VJ (r = -0.64 to -0.59), 20 and 40 yard sprint (r = -0.78 to – 0.57) in intercollegiate soccer players (n = 25) during an 11 wk regular season period.

Recent research has increased our understanding of the acute and short-term post-competition responses to contact sport participation, and the relationship between those measures, however uncertainty remains regarding the endocrine and neuromuscular response to elite Rugby League match-play. Concurrent assessment of endocrine and neuromuscular performance measures may therefore present an important means of monitoring the ability of elite Rugby League players to tolerate acute and chronic training and competitive loads. Furthermore, an increased understanding of the endocrine and neuromuscular responses to Rugby League match-play may provide scope for improved individualised training prescription and recovery strategies to avoid decrements in performance associated with the rigors of short turn-around times between matches, training and competition in the NRL.

2.5 Muscle Damage, Sports Performance and Recovery

2.5.1 Creatine Kinase (CK) and Skeletal Muscle Damage

Exercise induced skeletal muscle damage has been examined extensively in various forms of exercise in humans (132, 263, 334, 423), with damage observed following repeated sub-maximal SSC exercise (422), exhaustive endurance exercise (244, 338, 427, 478), a single bout of high force eccentric exercise (327, 440), resistance training (RT) protocols (35, 125, 336, 445, 483) and high intensity competitive team sports performance (11, 216, 401, 426). The extent of muscle damage has been related to the intensity and duration of exercise (439). Accordingly, high intensity eccentric exercise has traditionally been considered a primary factor associated with skeletal muscle damage (363).

Direct evidence of exercise induced skeletal muscle damage may include disruption of contractile tissue and subsequent morphological changes (including sarcolemma and Z-disc disruption, widening of A- and I- bands and displacement of organelles), and cellular accumulation of calcium (35, 57, 81, 132, 262, 363). Further, several indirect indicators of skeletal muscle damage following exercise have been observed, including delayed onset muscle soreness (DOMS), decreased muscular strength and range of movement (ROM) (80, 351), an increase in the appearance of muscle proteins such as myosin heavy-chain (MHC) fragments and / or myoglobin and elevated serum or plasma levels of intracellular enzymes such as glutamic oxaloacetic transaminase (GOT), lactate dehydrogenase (LDH), and creatine kinase (CK) (72, 73, 272, 333, 371, 463).

Creatine kinase (CK) is present in the human body as at least five isoforms with three iso-enzymes contained within the cytoplasm that are specific to skeletal muscle (CK-MM), cardiac muscle (CK-MB) and the brain (CK-BB) (57). In skeletal muscle tissue CK-MM accounts for 90-100 % of the total CK activity (57, 132). Within skeletal muscle tissue CK is located within the sarcolemma and mitochondrial inter-membrane space of healthy muscle cells and is responsible for catalysing the movement of phosphate from phosphocreatine (PCr) to adenosine diphosphate (ADP), forming adenosine triphosphate (ATP) and creatine (57, 77). Accordingly, CK is the primary enzyme associated with anaerobic metabolism (57). Creatine kinase is located almost exclusively within skeletal muscle tissue, therefore the serum or plasma CK activity is regularly used as an index of training or competition induced physiological stress (209, 320) and is most commonly reported as an indirect marker of skeletal muscle damage (64, 79, 132, 315, 355, 406, 407).

Numerous studies (11, 226, 259, 333) have reported a delay regarding the time course and mechanisms of efflux associated with increases in serum or plasma CK activity post-exercise and it would appear that the extent of such delay is determined by the type of exercise performed. Significant ($p < 0.05$) increases in CK activity have been observed immediately following exhaustive exercise in the form of 50 km cross-country ski racing (427) and 200 km ultra-marathon running (244). Additional investigations of marathon running (404, 478), downhill running (64, 406), repeated sport specific sprinting protocols (226) and competitive sports performance (11, 259) have revealed significant ($p < 0.05$) increases in serum or plasma CK activity within 3-6 hr post-exercise and peak CK activity in approximately 18-24 hr. Alternatively, following local muscular eccentric and sub-maximal isokinetic resistance exercise, significant ($p < 0.05$) increases in plasma CK activity have been delayed for up to 48-96 hr post-exercise (60, 310, 333-335, 337). The high intensity, intermittent nature of elite Rugby League match-play is associated with a complex interaction of repeated blunt force trauma and eccentric muscle actions during acceleration, deceleration, sprinting and SSC activity resulting in skeletal muscle damage. Accordingly, plasma CK activity may be expected to peak within approximately 24 hr of competition due to the high likelihood of skeletal muscle damage following elite Rugby League match-play.

The exact mechanism by which CK enters the circulation remains unclear (334), however it has been postulated that when acute damage occurs to the skeletal muscle cell structure, CK leaks into the interstitial fluid and the lymphatic system rather than being taken up by the capillaries due to the larger mass of the CK protein molecule (136, 383). Unlike the vascular system which contains a muscular layer within the vessels to assist the process of blood transport about the body, the lymphatic system relies on external forces to assist with the transport of fluids (383). Accordingly, the transport of fluid within the lymphatic system is relatively slow by comparison with the vascular system, requiring pressure changes during respiration and skeletal muscle activity to facilitate the CK transport process, which is eventually emptied back into the blood stream, resulting in a delayed increase and subsequent peak in plasma CK activity (132, 136). The post-exercise peak in plasma CK activity may be a consequence of slow transit through the lymphatic system, potentially taking several days to appear in the circulatory system, thereby reflecting both the CK release from damaged skeletal muscle tissue and it's clearance by the reticuloendothelial system (383, 436), and providing an indication of skeletal muscle damage following exercise.

Previous studies (60, 333, 335) have established the development of skeletal muscle damage following an acute bout of eccentric exercise, however when the same exercise is repeated several days or weeks after the initial exercise, decreased change in functional performance measures and intracellular enzyme activity that are indicative of skeletal muscle damage has been reported when compared to the first exercise bout (64, 80, 82, 133, 333, 337). The reduction in indirect markers of skeletal muscle

damage following subsequent exercise phenomenon is known as the repeated bout effect (RBE) (337). The RBE has been reported to influence CK activity post-exercise for several weeks (64) or may still be observed when a second bout of exercise is completed before full recovery from the first exercise bout has taken place (333, 337). A decrease in CK activity following the completion of a repeated exercise regime suggests that a prior bout of eccentric exercise provides a prophylactic effect, or protective mechanism against additional skeletal muscle damage from subsequent exercise (47, 337).

To demonstrate the RBE, Nosaka & Clarkson (333) showed that repeatedly performing an eccentric exercise protocol 3 days and 6 days after an initial bout of eccentric exercise did not exacerbate plasma CK activity as a criterion measure of skeletal muscle damage or interfere with the skeletal muscle repair process despite reductions in strength and ROM. Similarly, when a high force eccentric exercise protocol involving the elbow flexors (EF) was repeated 6 days following the initial bout of eccentric exercise, plasma CK activity as an indicator of skeletal muscle damage was not increased, notwithstanding residual muscle soreness and the presence of concomitant reductions in strength and ROM (133). Previous studies have demonstrated the RBE following bouts of down-hill running separated by 3, 6 and 9 weeks (64) while reductions in the plasma CK response to repeated local muscle maximal eccentric loading exercise have been identified from durations of several weeks (60, 82, 335) to as long as 6 months following the first bout of exercise (80).

During elite Rugby League training and competition, players undergo repeated high intensity eccentric muscle contractions during running, jumping and collision related movements, therefore the presence of residual muscle soreness associated with exercise induced muscle damage (EIMD) and DOMS is commonplace. Moreover, anecdotal evidence suggests that it is expected that players will experience increased muscle soreness and a reduction in muscle strength and ROM following match-play. The influence of EIMD and the RBE during extended seasons that involve weekly competition such the NRL season is of particular interest for sports scientists and strength and conditioning practitioners. Time frames between matches in the NRL may vary from 5-10 days with matches scheduled from Friday to Monday during each week of the competition. The variable match schedule may allow teams as few as 5 days recovery between matches, therefore it his highly likely that players will be required to take part in match-play while experiencing EIMD and muscle soreness from a previous match. The potential influence of the RBE and the pattern of response of indirect markers of muscle damage, such as plasma CK and reductions in muscle force are of interest to sports scientists and strength and conditioning coaches for the purposes of monitoring training load, match-play participation and recovery in elite contact sport such as the NRL.

2.5.2 Skeletal Muscle Damage and Sports Performance

The influence of EIMD, (which manifests itself as muscle soreness and a reduction in muscle function for several days post-exercise), and plasma CK activity on exercise and sports performance has received considerable attention for several decades (60, 81, 132, 139, 333, 334). Muscle fatigue in human performance may be defined as any exercise induced reduction in maximal voluntary force or power output produced by a muscle or muscle group (174). Accordingly, Warren et al., (463) have reported that measures of muscle function provide the most effective means of determining the magnitude and time course of damage resulting from eccentric muscle actions. Other researchers (63) have reported that functional impairments such as reductions in force and power represent the most important indicator of muscle damage when considering athletic performance in the presence of muscle damage.

A relationship between reduced performance of SSC activity and the inflammatory processes resulting from muscle damage has been reported (250). Recovery following SSC exercise has been reported (223, 326) to take place in a bimodal fashion, involving an acute post-exercise decline in skeletal muscle performance followed by a brief recovery and then a subsequent secondary drop 48 – 72 hr post exercise. The acute decline in skeletal muscle performance has been related primarily to metabolic disturbances that resolve within several hours, whereas the secondary decline in performance has been found to correspond to the presence of muscle enzyme release, such as CK in the blood, associated with phagocytic activity after an acute inflammatory response in the muscle (63, 146, 250). Secondary reductions in skeletal muscle performance coupled with increased plasma CK activity followed by subsequent reductions in CK activity between days 2 and 4 post-exercise and a corresponding increased muscle performance indicate a direct relationship between skeletal muscle damage, skeletal muscle performance and the respective recovery process post-exercise (250).

Reduced force and power production associated with EIMD has been reported following a wide variety of eccentric (62, 139, 336, 351, 399) and dynamic SSC (208, 222, 223, 226, 327, 436) exercise protocols. Fewer studies (35, 71, 440) have found no decrement in the functional capacity of skeletal muscle in response to EIMD. In an investigation of EIMD and CK activity on isometric KE MVC and a 30 s Wingate cycle test, Byrne and Eston (62) evaluated each criterion measure before, 1 hr after and 1, 2, 3 and 7 days following a bout of eccentrically biased resistance exercise consisting of 10 sets of 10 reps (100 reps) of barbell squats performed at 80 % concentric 1RM (n = 7). The results of Byrne and Eston (62) revealed an immediate and long-lasting reduction in the ability to generate isometric force and dynamic peak power. The eccentric exercise protocol resulted in a significant ($p < 0.05$) increase in plasma CK activity after 1 hr, that remained elevated for 2 days with peak CK activity determined 1 day post exercise (808 ± 117 $U.L^{-1}$). Isometric KE MVC was significantly reduced (p

< 0.05) 1hr after exercise and remained so for 7 days while Wingate test performance was also reduced at all post-exercise test intervals, but only significantly ($p < 0.05$) so 1 day post-eccentric exercise. Although the time course of MVC and Wingate assessments were equal, the two variables differed in their pattern of recovery. Linear improvements in MVC were evident over the course of the 7 day recovery period while prolonged decrements in PP during the Wingate test were identified for up to 48 hr post-exercise prior to subsequent improvements in dynamic muscle performance. Byrne and Eston (62) attributed the biomodal pattern of muscle recovery to inflammatory and neuromuscular responses (in the form of reduced central drive resulting from subconscious reflex mechanisms associated with peak DOMS) to EIMD. The findings of Byrne and Eston (62) highlight the importance of monitoring peripheral mechanisms associated with muscle force-generating structures and other performance measures that are indicative of centrally mediated neuromuscular fatigue following exercise that is characteristic of inducing muscle damage, such as elite Rugby League match-play. A better understanding of the time course associated with the recovery of peripheral and centrally mediated fatigue as markers of muscle damage following elite Rugby League match-play may be beneficial to determine post-match training protocols in preparation for subsequent competition.

Reductions in the force generating capacity of muscle following EIMD resulting from a variety of eccentric exercise protocols have been reported (139, 336, 351, 399). Endoh et al., (139) examined the effects of muscle damage induced by eccentric exercise on muscle fatigue and reported significant ($p < 0.001 – 0.05$) reductions in sustained elbow flexor (EF) isometric MVC (n = 10) for up to 4 days post-exercise. Endoh et al., (139) attributed decrements in muscle force production following a bout of repeated maximal eccentric elbow extension (EE) exercise to peripherally mediated muscle damage. The results of the work of Endoh et al., (139) are consistent with the findings of Nosaka and Newton (336) who identified significant ($p < 0.01$) reductions in EF isometric MVC for up to 5 days post-maximal but not sub-maximal eccentric EE exercise with corresponding increases ($p < 0.01$) in CK activity and muscle damage. Additional studies (351, 399) that have examined the force generating ability of skeletal muscle following high intensity eccentric lower limb exercise have reported significant ($p < 0.05$) reductions in knee extension (KE) isometric MVC and increased CK activity ($p < 0.05$) as indicators of muscle damage for up to 96 hr post-exercise.

The influence of increased plasma CK activity as an indicator of EIMD, and SSC performance has been extensively examined (208, 222, 223, 326, 327, 422) to monitor acute and short-term neuromuscular fatigue and recovery post-exercise. It has been proposed that a relationship exists between reduced SSC performance and muscle damage following exhaustive SSC exercise (222, 250). In studies that examined drop jump (DJ) performance following exhaustive SSC muscle damage induced exercise on a inclined sledge apparatus, Horita et al., (222, 223) reported bimodal patterns of muscle recovery corresponding with post-exercise CK activity. In an analysis of exhaustive SSC

exercise on the time-course of mechanical behaviour during the DJ and the role of muscle damage, Horita et al., (223) reported significant reductions ($p < 0.01$) immediately and 2 hr after DJ performance (n = 10) followed by an early recovery and a secondary decline 2 days post exercise with concurrent initial (immediately after – 2 hr) and secondary (2hr – 2 days) increases in CK activity. Horita et al., (223) reported that reductions in DJ performance after exhausting SSC exercise accompany the progress of muscle damage observed by corresponding increases in CK activity, thereby supporting the incorporation of functional muscle performance analysis to reflect recovery following EIMD.

Using a similar study design to that previously reported (223), Horita et al., (222) examined the influence of EIMD following exhaustive SSC sledge-jumping exercise on concentric muscle function immediately following SJ and DJ performance and then at subsequent testing intervals of 10 min, 20 min, 2 days and 4 days post-exercise (n = 10). The results of Horita et al., (222) identified an immediate ($p < 0.001$) reduction in SJ PP performance that recovered within 10 min post-exercise and remained stable for the remainder of the test schedule. In contrast, a delayed and significant ($p < 0.01$) reduction in DJ PP was found on days 2 and 4 post-exercise and corresponded with markedly elevated CK activity on the 2nd and 4th day following exercise. Horita et al., (222) proposed that SSC exercise induces both acute metabolic fatigue, as evidenced by immediate reductions in SJ performance, and delayed muscle damage as depicted by the delayed increase in CK activity and concurrent reductions in DJ performance. The findings of Horita et al., (222, 223) therefore support the findings of other researchers (208) that have suggested DJ, CMJ and SJ performance analysis may reflect muscle damage following exhaustive SSC exercise.

Field sports involving repeated sprinting such as Rugby League, Soccer and Australian Rules Football are characterised by periods of high-intensity running interspersed with short distances of deceleration, changes of direction and lower-intensity jogging and walking (408). Despite the popularity of sports involving multiple sprint activities, few studies (226, 391, 436) have investigated EIMD following high-intensity repeated sprint protocols. Recently, Howatson and Milak (226) examined isometric KE MVC force of the lower limb, muscle soreness and serum CK activity immediately before, and at 24 hr, 48 hr and 72 hr after 15 x 30 m maximal sprints with a 10 m deceleration zone separated by a 60 s rest period between each sprint (n = 20). The results of Howatson and Milak (226) revealed significant ($p < 0.05$) reductions in lower limb force production at 24 hr and 48 hr post exercise while a peak ($p < 0.001$) in CK activity was found 24 hr after the repeated sprint bout, and remained elevated following 48 hr ($p < 0.001$) and 72 hr ($p < 0.004$) of recovery. All dependent variables showed significant change over time, indicting that the repeated sprint protocol coupled with an eccentric deceleration component elicited muscle damage that remained for at least 72 hr post-exercise. Howatson and Milak (226) concluded that the repeated sprint protocol with rapid deceleration may be

used as a suitable alternative to examine the muscle damage response from a sport specific bout of high-intensity sprint mode of exercise and may provide insight to the anticipated muscle damage response to repeated sprint profiles characteristic of elite Rugby League match-play.

The impact of prolonged intermittent high-intensity shuttle running on muscle soreness and markers of muscle damage have been examined (436) to replicate the repeated sprint activities commonly experienced by participants of field based sports. Using the Loughborough Intermittent Shuttle Test (LIST) that involves 90 min of sprinting, jogging and walking, Thompson et al., (436) examined muscle soreness and CK activity before and after the exercise period and at intervals of 24 hr, 48 hr and 72 hr post exercise (n = 16). Thompson et al., (436) found significant ($p < 0.05$) increases in CK activity immediately post-exercise that remained above baseline for 48 hr ($p < 0.05$) with peak values recorded the day after the LIST protocol. General muscle soreness remained elevated for 72 hr following the shuttle test ($p < 0.05$) peaking 24-48 hr ($p < 0.05$) post-exercise. Although muscle soreness and CK were elevated over similar time frames post-exercise, the two parameters were not significantly correlated and thereby support the implementation of quantifiable markers of muscle damage, such as CK activity, rather than subjective ratings of perceived soreness to evaluate the response to athletic performance and monitor subsequent recovery. The findings of Thompson et al., (436) provide further evidence to suggest that sports involving bouts of high-intensity intermittent sprint activity interspersed with periods of low-intensity work such as elite Rugby League match-play have the potential to induce muscle damage and compromised functional performance.

In contrast, Semark et al., (391) examined the effects of EIMD on sprint performance and reported no significant decrement in CK activity measured before and 12, 24, 48 and 72 hr after a bout of 3 x 30 m sprints followed by 7 x 10 drop jumps. Although subjects (n = 25) reported significantly ($p < 0.05$) more pain following 24 hr and 48 hr recovery CK was unchanged, suggesting the exercise bout did not induce skeletal muscle damage to a degree capable of producing a deleterious influence on performance. Similarly, other researchers (440) have reported increased muscle soreness ($p < 0.05$) and elevated CK activity ($p < 0.01$) for up to 48 hr and 72 hr respectively following high-volume lower limb plyometric exercise without a concomitant decrease in isometric KE MVC post-exercise (n = 18) . The absence of impaired muscle performance despite the presence of muscle damage reported by Tofas et al., (440) is unexpected, and highlights limitations associated with subjective pain reporting measures to monitor recovery and the importance of functional performance measures to determine potential decrements in force and power generating capacity of muscle following a bout of repeated high-intensity SSC exercise.

Studies (222, 226) have demonstrated that EIMD has a negative effect on measures of force and power associated with athletic performance, however less is known regarding the influence of EIMD on

endurance running. Marcora and Bosio (293) examined muscle soreness, CK activity and KE isometric MVC before, and 48 hr after muscle damaging DJ exercise (n = 30) that was followed by 10 min of sub-maximal running at 70% VO_2 max and a 30 min running time trial. Marcora and Bosio (293) reported significant reductions in KE isometric strength ($p < 0.001$), time trial running speed ($p = 0.02$) and overall time trial performance ($p < 0.01$) that corresponded with prolonged elevations in CK activity ($p < 0.006$) 48 hr following the initial bout of muscle damaging exercise. The work of Marcora and Bosio (293) confirmed their hypothesis that EIMD impairs endurance running performance in trained runners and endorses the philosophy that athletes should not perform muscle damaging activities such as high-intensity plyometric training, downhill running or high-volume resistance training in the days preceding endurance running tasks, such as that required of players during elite Rugby League match-play.

Currently, there is limited information regarding performance and muscle damage responses occurring within the standard 6 day period between competitive high-intensity sports performance completed on a weekly basis. Recently, Ispirlidis et al., (228) completed a comprehensive analysis of the time-course of changes in muscle damage (serum CK activity) and performance responses (1RM squat, 20 m sprint and CMJ performance) 2 hr prior, immediately following and 24, 48, 72, 96, 120 and 144 hr following elite soccer (n = 24) match-play. The results of Ispirlidis et al., (228) revealed a general deterioration of muscle performance for up to 4 days post-match with significant reductions ($p < 0.05$) in CMJ and 1RM squat for up to 72hr and 96 hr post-match respectively. Sprinting ability also declined significantly ($p < 0.05$) for 72 hr following match-play, with peak reduction sprint performance recorded 48 hr post-match followed by a progressive return to pre-match levels following 120 hr of recovery. By comparison, CK activity increased ($p < 0.05$) immediately post-match (+ 400 %; 400 $U.L^{-1}$), peaked 48 hr after the game (+ 710 % ; 950 $U.L^{-1}$) and required 5 days to return to pre-match levels. The results of Ispirlidis et al., (228) confirm that soccer match-play, despite an absence of collisions between players, induces time-dependent changes in various performance and muscle damage markers that were comparable with contact sport participation (304, 426). Accordingly, the findings of Ispirlidis et al., (228) indicate that players may not be able to perform high-intensity force, power or anaerobic tasks at maximum capacity for a minimum of 3 days following competition. Training volume and intensity may therefore need to be closely monitored for a minimum of 5 days following elite soccer match-play to avoid exacerbation of muscle damage and subsequent decrements in performance.

In a similar study that investigated neuromuscular fatigue and recovery associated with active versus passive recovery following elite soccer match-play (n = 22), Andersson et al., (11) examined CMJ, sprint performance, isokinetic KF and KE and CK activity before, immediately after, and 5, 21, 45, 51 and 69 hr post-match. The results of Andersson et al., (11) are consistent with the findings of other

researchers (228), revealing immediate post-match reductions and time-dependent recovery of neuromuscular parameters in the form of isokinetic KE (27 hr), KF (51 hr), 20 m sprint (5 hr) and CMJ (74 hr) (all $p < 0.05$) with immediate and prolonged increases in CK activity ($p < 0.05$) for 3 days post-match. Andersson et al., (11) concluded that acute decrease in CMJ and sprint performance, together with reduced isokinetic strength are influenced by the presence of muscle damage and the manifestation of peripheral and central components of fatigue following soccer match-play. The asynchrony of recovery of CMJ and isokinetic strength following soccer performance confirm the independent nature of these test parameters in response to high-intensity, repeated sprint activity that is characteristic of soccer and Rugby League competition. The findings of Andersson et al., (11) support the inclusion of functional muscle analysis in the form of SSC activity to monitor post-match recovery and endorse the work of other researchers (228, 271) that have included CMJ and CK activity to monitor fatigue following match-play to monitor elite soccer players tolerance of training and competitive loads.

2.5.3 Creatine Kinase (CK) and Recovery Following Contact Sports Performance

The combative nature of Rugby League match-play combined with intermittent high intensity activity during competition are synonymous with repeated blunt force trauma, micro-damage to skeletal muscle and post-exercise soreness. Although eccentric muscular work has traditionally been considered the predominant contributor to increased CK activity after exercise (57) recent evidence (216, 401) suggests that increased plasma CK activity may occur as a result of physical collisions and blunt force trauma. Elevated plasma CK activity has been reported following competitive match-play in contact sports (111, 179, 216, 259, 401, 426) suggesting that skeletal muscle damage occurs during such contact sports. The CK response to elite Rugby League match-play however is unknown.

Recently, Kraemer et al., (259) examined markers of skeletal muscle damage and circulating anabolic and catabolic hormones to gain insight into the recovery process following an American Football match (n = 28) performed in week 11 of a National Collegiate Athletic Association (NCAA) Division 1 season. Endocrine and serum CK activity was measured the day before the match, 18-20 hr after the match and 42-44 hr post-match. The primary finding of Kraemer et al., (259) revealed significantly ($p < 0.05$) increased CK activity 18-20 hr after participation in a college match of American Football followed by a return to pre-match baseline values by 42-44 hr post-match. Kraemer et al., (259) noted that while CK increased 41 % from baseline to 18-20 hr post-match, (233.7 ± 198.5 to 330.5 ± 153.4 $U.L^{-1}$) CK activity was substantially lower than those reported after two-a-day practices during a pre-season American Football training camp (136). The discrepancy between relatively high CK values reported by Ehlers et al., (136) during a pre-season training camp and following match-play (n = 12) in

the 11th week of a regular season period may reflect the concept of 'contact adaptation' throughout the course of the American Football season that reportedly minimises the degree of muscle damage after repeated trauma during practices and match-play (136, 215) . An overview of the response of anabolic and catabolic endocrine measures has been provided previously in the present review. The work of Kraemer et al., (259) provides further evidence of the incorporation of CK analysis to monitor the demands of contact sport match-play and subsequent recovery patterns following competition.

In an additional analysis of the performance and biochemical responses during an intercollegiate American Football match (n = 21), Hoffman et al., (216) examined PRFD, PF and PP during SJ and CMJ approximately 10 min before kickoff and following the first, second, third and fourth quarters of the match. To determine muscle tissue damage and physiological stress in the players, blood samples were obtained for the analysis of CK activity 24 hr and 2.5 hr before the match and within 15 min of match-completion. In contrast to the findings of other researchers (177, 259), no significant changes in CK activity were observed following American Football match-play. Further, significant ($p < 0.05$) performance decrements of PF and PP during SJ and CMJ were observed within the first quarter and continued to decline ($p < 0.05$) until a plateau in the reduction of PF and PP at half-time. Remarkably, both PF and PP during the SJ and CMJ returned to pre-match levels by the completion of the fourth quarter while a similar but not significant trend of progressively reduced PRFD during the first half of the match was observed followed by a return to baseline by the completion of the match. It would therefore appear that despite the highly physical nature of American Football competition, players are afforded sufficient rest throughout the course of match-play to facilitate physiological and neuromuscular recovery process. Alternatively, the results of Hoffman et al., (216) may reflect player adaptation to contact or that the intensity of match-play produced a less fatiguing effect on eccentric muscle loading and neuromuscular factors associated with the performance of SSC activities such as the CMJ. The results of Hoffman et al., (216) raise questions regarding the appropriateness of comparisons between performance measures and muscle damage outcomes during American Football competition and following elite Rugby League match-play where considerable variation exists regarding the opportunity players have to recover during the course of a match.

Traditionally, comparisons between the sports of Rugby League and Rugby Union have taken place on the basis of perceived similarities between the physical characteristics of match-play and the widely held view that both sports are considered to be two of the most physically demanding field based team sports at the elite level. Accordingly, studies (110, 179, 401, 424, 426) that have examined the time course of changes in biochemical, endocrine and neuromuscular indicators of performance and fatigue following Rugby Union match-play may provide insight into the response of such parameters to Rugby League competition and the effectiveness of recovery strategies post-match.

Several studies have examined the influence of Rugby Union match-play on skeletal muscle damage in collegiate (424) and professional (179) players. Suzuki et al., (424) examined the influence of active versus passive recovery methodologies on muscle damage before, after and days 1 and 2 following collegiate Rugby Union (n = 15) match-play. The results of Suzuki et al., (424) found increased ($p < 0.05$) CK activity immediately post-match followed by a peak in CK activity 24 hr (715 ± 438.3 $U.L^{-1}$) post-match and a return to baseline on day 2 following the match in both groups. While CK activity remained elevated ($p < 0.05$) on day 2 post-match, no significant differences were noted between active (undisclosed low-intensity aquatic exercise) and complete rest on the behaviour of CK activity post-match.

In an analysis of professional players, Gill et al., (179) incorporated an examination of CK activity to reflect the magnitude of skeletal muscle damage and to determine the effectiveness of recovery strategies following elite Rugby Union (n = 23) match-play. The results of Gill et al., (179) found significant increases ($p < 0.01$) in interstitial [CK] from pre- to post-match with levels of 1023.0 ± 308.3 $U.L^{-1}$ and 2194.0 ± 833.7 $U.L^{-1}$ respectively and confirm the findings of other researchers (110, 401, 424, 426) that the exercise and collisions experienced by players during Rugby Union match-play are sufficient to elicit a significant increase in [CK]. Of particular note, Gill et al., (179) attribute the involvement of direct impact between opposing players during competition to be the primary cause of elevated [CK] found in elite Rugby Union players following match-play.

The influence of blunt force trauma associated with collisions with opposition players during Rugby Union match-play has been investigated (426) to determine the time course of muscle damage and subsequent recovery, and to enable coaches and strength and conditioning professionals to prescribe appropriate and individualised training programs for subsequent performance. Accordingly, Takarada (426) evaluated muscle damage following Rugby Union match-play (n = 15) with special reference to the influence of contact during tackle plays examined CK activity 48 hr before, immediately after and at intervals of 45 min, 90 min, 24, 48 and 72 hr following an match involving elite college level players. The results of Takarada (426) confirmed that competitive Rugby Union match-play induces substantial structural damage to muscle tissue, with appreciable transient increases in CK activity after the match culminating in peak CK activity (1081 ± 159 $U.L^{-1}$; $p < 0.05$) 24 hr post-match and a return to baseline following 72 hr of recovery. Of particular interest regarding comparative analysis between the influence of contact on muscle damage markers and recovery, a significant correlation ($r = 0.92$, $p < 0.01$) between the number of tackle involvements and peak CK activity was identified 24 hr post-match. The findings of Takarada (426) corroborates the results of other researchers (179, 401) that participation in high-intensity contact sport, such as Rugby Union and Rugby League result in considerable muscle tissue damage. While the contribution of eccentric muscle activity on the amount of muscle damage experienced by players as a result of high-intensity running during Rugby Union

match-play has been established (226, 436), the work of Takarada (426) is the first to substantiate a link between the extent of muscle damage and the contribution of blunt force trauma during collisions in Rugby Union.

Recently, the relationship between CK activity and match-related impacts in elite Rugby Union has received further attention from researchers (110, 401). Using a single group, multi-match repeated measures pre to post-match design, Smart et al., (401) examined impact related match statistics and interstitial [CK] approximately 3.5 hr before and within 30 min following a series of National Provincial Championship (NPC) semi-professional (n = 23) Rugby Union matches. Following match-play [CK] increased from pre- to post-match in a position specific manner with forwards experiencing significantly ($p < 0.05$) higher (1439 ± 204.2 $U.L^{-1}$) [CK] in comparison to backs (545.4 ± 340.6 $U.L^{-1}$) with mean post-match [CK] of 926.8 ± 204.2 $U.L^{-1}$. In order to determine which impact related factors influenced the [CK] difference between forwards and backs, Smart et al., (401) used regression equations to reveal correlations between a number of impact-specific match statistics, including game time (r = 0.69 and 0.82 respectively), time defending (r = 0.72 and 0.74 respectively), total hit-ups (r = 0.74), scrum number (r = 0.73) for forwards and the number of times a player was one of the first three players to a ruck play in attack (r = 0.79) for backs. The results of Smart et al., (401) provide additional confirmation that blunt trauma and physical collisions during Rugby Union match-play elicit substantial skeletal muscle damage that is dependent on playing position. Further, regression equations may enable changes in [CK] to be predicted and to provide an indication of muscle damage to assist coaches and strength and conditioning professionals to monitor workload and training to optimise recovery and subsequent performance.

An important link between the degree of muscle trauma and match-specific collisions is further established by Cunniffe et al., (110) following their analysis of the time-course of serum CK during international level (n = 10) Rugby Union match-play. To determine the level of muscle damage in players, venous blood samples were collected on the morning of the match (pre), 15 min after (post) and again on the mornings of day 1 (14 hr post) and day 2 (38 hr post) following match-play. Increased CK activity ($p < 0.05$) was observed 14 hr (1182 ± 231 $U.L^{-1}$) and 38 hr (750 ± 99 $U.L^{-1}$) following the match with values 14 hr post significantly ($p < 0.05$) higher than those found pre, or immediately post-match. Significant correlations were also observed between the number of contact events (r = 0.78; $p < 0.05$) and tackles (r = 0.86; $p < 0.05$) completed by players and serum CK activity on morning of day 2 post-match. Significant correlations between contact events (r = 0.65; $p < 0.05$) and tackle number (r = 0.63; $p < 0.05$) were also observed with CK activity 14 hr post-match (110). The results of Cunniffe et al., (110) are consistent with other researchers (11, 228, 426) that have reported a delayed increase in CK activity following contact sport competition. The work of Cunniffe et al., (110) indicate that Rugby Union match-play elicits a blunt trauma effect on muscle damage and

a concomitant influence on CK activity and substantiates the inclusion of CK as a meaningful measure to monitor the demands of high intensity contact sport match-play.

2.6 SUMMARY

Despite the popularity of the NRL as a spectator sport and the professional status of elite players, the scientific examination of elite Rugby League match-play has been relatively neglected. To date our basic understanding of the physiological demands of match-play has primarily been based on empirical observation and deduction. There have been only limited attempts to examine the acute and short term post-match recovery period physiological responses of elite players to competition. Accordingly, the predominance of sport science research examining the sport of Rugby League has been limited to arbitrary reporting of injury rates during training and retrospective analysis of the physiological and anthropometric characteristics of players at amateur, semi-professional and professional levels. The focus of the present research therefore is to provide insight into the neuromuscular, endocrine, biochemical and physiological responses of players' pre, during and following elite Rugby League match-play.

The paucity of scientific data available on the physiological stressors associated with match-play in the NRL are likely related to the inaccessibility of elite players during match-play. The intensity of competition and the chaotic atmosphere that may exist in the change rooms post-match (e.g. player media commitments, rehydration, refuelling and active recovery protocol participation, injury assessment and management, euphoria of success versus disappointment of a loss) generally creates an environment in which data collection is problematic. However, the present research was successfully completed in a unique sporting environment with unprecedented access to elite Rugby League players participating in the NRL.

There is increasing evidence that greater plasma CK activity may result from physical impact and blunt force trauma during contact sport match-play, however the time-course of changes in endocrine and skeletal muscle damage markers following elite Rugby League match-play is unknown. Accordingly, a greater understanding of the physiological, endocrine and biochemical responses to elite Rugby League match-play and recovery may provide increased scope for improvement in individualised post-match strategies, reduce the risk of residual and or cumulative fatigue and potentially decrease the incidence of acute and chronic musculoskeletal injury.

CHAPTER 3

THE ROLE OF RATE OF FORCE DEVELOPMENT ON VERTICAL JUMP PERFORMANCE

3.1 Introduction

The vertical jump (VJ) is often used as a performance test to assess athletic ability, identify athletes strengths and weaknesses and measure the effectiveness of training programs (206, 382). The VJ performance is determined by a complex interaction among several factors, including the maximal force developed by the musculature involved, the rate at which force can be developed, and the neuromuscular coordination of the upper and lower body segments (221, 384). To measure the contribution of these factors, different protocols and devices have been used, including the use of contact mats, position transducers, V-scopes, accelerometers, rotary encoders, yardsticks and force plates (70, 107, 207, 292, 295, 416). Common performance measures calculated from these devices are peak power (PP) or average power (AP). While force plates are considered the "gold standard" in force measurement (329), force plates are expensive and not easily accessible outside the laboratory setting.

The VJ height has been widely used by sports performance professionals as an alternative to direct assessment of maximal force and power (67, 206, 384). Recently, the validity of predicting peak and average power on the basis of VJ height has been challenged (107, 187, 469). Furthermore, the use of the term "power" as a mechanical construct to indicate maximal exercise performance is unclear, with strength qualities such as rate of force development (RFD), impulse and explosive strength being suggested as a better predictor of athletic ability and performance (105). The RFD is the development of maximal force in minimal time, and is typically used as an index of explosive strength (484).

Although RFD has been shown to be an important performance variable by some investigators (176, 199, 467, 468), others have reported a poor relationship between RFD and the VJ (195, 292, 450). Indeed, Marcora et al., (292) found no significant correlation between RFD and VJ performance measured during an isometric contraction in a horizontal squat position. The lack of a significant relationship between RFD and the VJ may be due to methodological problems associated with the measurement of RFD. Confounding factors include separate tests (450) when examining the relationship between RFD and the VJ and the inclusion of both male and female subjects in the

assessment of RFD and VJ performance (195). Recently, Kawamori et al., (238) reported a correlation, albeit a non-significant one, between dynamic RFD and VJ performance (r = 0.65 - 0.74). The lack of significant correlation between RFD and VJ was most likely caused by low statistical power (n = 8). To resolve the problem of low statistical power, the present study used 23 males to determine the relationship between RFD and VJ. Therefore, aim of the present study was to examine i) the relationship between RFD and VJ performance during a CMJ, ii) the reliability of RFD data recorded during the CMJ and SJ forms of the VJ. It was hypothesized that there would be a significant correlation between RFD and VJ performance, suggesting that the ability to develop force quickly enhances VJ height. However, the use of RFD as a performance measure may not provide the reliability needed for field based athlete testing.

3.2 Methods

3.2.1 Experimental Approach to the Problem

Subjects attended the Sport Science Laboratory on two separate occasions to participate in a familiarization session and a testing session. The test session consisted of a warm up that included a series of cycle ergometry and dynamic range of movement activities prior to subjects randomly completing three CMJ and three SJ on a force plate. During the CMJ, subjects utilized the stretch shortening cycle and incorporated arm swing into the movement to achieve a maximal jump and reach to record vertical jump height. During the SJ, subjects started the vertical jump from a stationary semi squat position with both hands held on the hips throughout the full range of movement. Independent t-tests and correlation coefficients were used to analyse the force time variables from the force plate during the CMJ and SJ movements. Force time variables analysed during the CMJ and SJ included peak force (PF), time to peak force (TPF), peak rate of force development (PRFD), average rate of force development (ARFD), peak power (PP) and average power (AP). Vertical jump displacement (VJD) was measured during the CMJ only, determined as the difference between standing reach and jump reach height.

3.2.2 Subjects

Twenty three physically active men volunteered to participate in this study. None of the men who participated in the present study were experienced in explosive exercise, none were resistance trained and none of the subjects were participating in regular resistance training prior to data collection. The

subjects were considered to be physically active on the basis that they were actively involved in recreational sports such as Australian Rules Football, Soccer and Rugby Union, in which jumping activities are typical of match play. Subject descriptive data is listed in Table 3. Prior to participating in the present study, all subjects completed Physical Activity Readiness Questionnaire (PAR-Q) and medical history questionnaires and gave written consent in accordance with the guidelines set forth by the Bond University Human Research Ethics Committee (BUHREC). All subjects who participated in the present study attended a familiarisation session three days prior to testing. During that familiarization session subjects received instruction in relation to the performance of the CMJ and SJ and completed the same protocol used in testing. Subjects were asked to refrain from strenuous exercise for 48 hr before the testing session.

Table 3. Descriptive characteristics of subjects (n = 23).

Variable	Mean	SD
Age (yr)	23.0	± 3.9
Height (cm)	179.5	± 9.9
Body mass (kg)	81.0	± 10.5

3.2.3 Procedures

3.2.4 The Vertical Jump

Prior to performing the unloaded CMJ and SJ tests, subjects completed a warm-up consisting of 10 minutes of self paced cycling on a stationary cycle ergometer followed by 5 minutes of prescribed dynamic stretching. Once positioned on the force plate, subjects performed 1 submaximal practice jump for both the CMJ and SJ. Each subject then performed 6 vertical jumps (3 CMJ and 3 SJ) beginning with either the CMJ or SJ, then alternating between jumps with 3 minutes rest between each jump. Displacement for each CMJ was measured with a Vertec (SWIFT Performance Equipment, Lismore, Australia) and has been described previously (195, 249). To establish standing reach height each subject stood side-on to the Vertec jumping device while keeping the heels on the floor and reached upward as high as possible to displace the zero reference vane.

Each subject commenced the CMJ in the standing position, dropped into the squat position and then immediately jumped vertically, incorporating arm swing to jump as high as possible displacing the vane at the maximum height of the jump. The depth of knee flexion and the amount of arm movement used during each CMJ was individually determined by each subject. Take-off from two feet was

strictly monitored with no preliminary steps or shuffling permitted during the eccentric or transition phases of the CMJ technique. The distance between the standing reach and maximum jump height reached on the Vertec to the nearest centimetre (cm) was taken as the VJ displacement (VJD) for the CMJ. The SJ technique required the subject to descend to a position of 90º knee flexion, determined using a hand held goniometer, that positioned the upper thigh parallel with the ground (195). Subjects were instructed to hold this position for 3 seconds, after which time the subject jumped for maximum height without prior countermovement. All SJ were executed with both hands on the hips throughout the full range of take off, flight and landing movements. The best result from each of the CMJ and SJ protocols was used for analysis. Both the CMJ and the SJ were performed on a force plate (ONSPOT 2000-1) which sampled at a rate of 1000 Hz and the analogue signal was converted to a digital signal using a PowerLab 30 series data acquisition system (ADInstruments, Sydney, Australia). The vertical force-time data were filtered using a fourth-order Butterworth low-pass filter with a cutoff frequency of 17 Hz (482).

3.2.5 Calculation of Force Variables

The force-time data examined during the CMJs and SJs included peak force (PF), peak rate of force development (PRFD), average rate of force development (ARFD), time to peak force (TPF), peak power (PP) and average power (AP). A jump was deemed to have started when the vertical force exceeded 10 N greater than the mass of the subject. The PF was calculated as the maximum force achieved over the force-time curve during the jump. The PRFD was calculated from the maximum force that occurred over the first derivative of the force-time curve. The ARFD was calculated as the peak force divided by the time taken to achieve the peak force. The TPF was taken as the time from the commencement of the jump until PF was reached. The vertical velocity that was calculated from the integration of the force-time trace was used in the calculation of PP and AP. The vertical force was multiplied by the velocity throughout the propulsive phase of the jump, yielding power. The maximum value was taken as PP with total work during the propulsion phase divided by the time of the propulsion phase to provide a measure of AP.

3.2.6 Statistical Analysis

The FTVs analysed during the CMJ and SJ included VJD, PF, TPF, PRFD, ARFD, PP and AP. The data are represented as mean and standard deviation (*SD*). Independent *t*-tests were used to analyse the FTVs between the CMJ and SJ with the level of significance set at $p \leq 0.05$. Any significant

differences were identified using Tukey's honestly significant difference (HSD) test. Pearson's product moment correlation coefficients were used to determine the relationship between force-time variables and vertical jump performance. Within-subject variation and reliability for VJD and force-time variables was determined by calculating the coefficient of variation (CV), confidence limits (95 %) and intra class correlation coefficients (ICC) as described by Hopkins (220). All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS for Windows, version 11.0; SPSS, Inc., Chicago, IL).

3.3 Results

The mean (± SD) values for the CMJ and SJ are presented in Table 4. The PP ($p = 0.007$) and AP ($p = 0.006$) were significantly higher during the CMJ than during the SJ. There were no other significant differences in performance measures during the CMJ and SJ. Tables 5 and 6 provide the calculated CV and ICC along with the associated 95 % confidence limits for each of the force-time variables recorded during the CMJ and SJ respectively. For both CMJ and SJ movements, PF, PP and AP all demonstrated high test-retest reliability (CV range: 2.8 - 5.1 %) and high test-retest correlations (ICC range: 0.91 - 0.99). The VJD demonstrated high test-retest reliability for the CMJ (ICC: 0.98) with low within-individual variation (CV: 3.3 %). TPF, PRFD and ARFD for the CMJ and SJ demonstrated low test-retest reliability (CV range: 11.8 - 17.9 %) and test-retest correlations (ICC range: 0.72 - 0.97).

The interrelationship between force-time variables for the CMJ and SJ are presented in Table 7 & 8. A significant relationship ($r = 0.68$; $p = 0.001$) between VJD and PRFD can be observed for the CMJ. There were significant relationships between VJD, PP and AP during the CMJ (Table 7). TPF during the CMJ was significantly related to PRFD and ARFD respectively (Table 7) for the SJ however during the CMJ TPF was significantly related to PRFD only (Table 8). PRFD was also significantly related to PF, ARFD and AP for both VJ methods (Table 7 & 8). With the exception of TPF, PF showed significant relationships will all force time variables measured for both the CMJ and SJ (Tables 7 & 8).

Table 4. Performance characteristics during the countermovement jump (CMJ) and squat jump (SJ) (n = 23).

Variable	CMJ	SJ
Vertical jump displacement (m)		
Mean	0.55	-
SD	± 0.1	-
Peak force (N)		
Mean	1972	1825
SD	± 358	± 273
TPF (ms)		
Mean	239	197
SD	± 65	± 71
PRFD ($N \cdot s^{-1}$)		
Mean	10728	9718
SD	± 4014	± 3380
ARFD ($N \cdot s^{-1}$)		
Mean	4790	4375
SD	± 2155	± 1809
Peak power (W)		
Mean	4774*	4056
SD	± 722	± 675
Average power (W)		
Mean	2359*	1990
SD	± 456	± 401

TPF = time to peak force; PRFD = peak rate of force development; ARFD = average rate of force development; * denotes significance at $p < 0.01$

Table 5. Coefficients of variation (CV), intraclass correlation coefficients (ICC), and associated 95 % confidence limits for the force-time variables during the countermovement jump (CMJ) (n = 23).

Variable	CV %	95% Confidence Limits		ICC	95% Confidence Limits	
		Lower	Upper		Lower	Upper
Vertical jump disp. (m)	3.3	2.6	4.7	0.98	0.92	0.99
Peak force (N)	3.5	2.8	4.6	0.97	0.91	0.99
TPF (ms)	11.8	9.4	15.8	0.90	0.74	0.97
PRFD ($N \cdot s^{-1}$)	16.3	13.7	20.4	0.89	0.77	0.95
ARFD ($N \cdot s^{-1}$)	17.9	14.2	24.2	0.89	0.72	0.96
Peak power (W)	2.8	2.1	4.0	0.97	0.97	0.99
Average power (W)	3.7	2.8	5.3	0.97	0.93	0.99

Disp = displacement; TPF = time to peak force; PRFD = peak rate of force development; ARFD = average rate of force development.

Table 6. Coefficients of variation (CV), intraclass correlation coefficients (ICC), and associated 95 % confidence limits for the force-time variables during the squat jump (SJ) (n = 23).

Variable	CV %	95 % Confidence Limits		ICC	95% Confidence Limits	
		Lower	Upper		Lower	Upper
Peak force (N)	2.8	2.3	3.6	0.97	0.92	0.99
TPF (ms)	13.2	10.6	17.5	0.88	0.70	0.95
PRFD ($N \cdot s^{-1}$)	14.8	11.9	19.5	0.89	0.75	0.96
ARFD ($N \cdot s^{-1}$)	16.9	13.4	22.8	0.89	0.73	0.96
Peak power (W)	3.4	2.6	4.8	0.96	0.91	0.99
Average power (W)	5.1	3.9	7.4	0.94	0.87	0.98

TPF = time to peak force; PRFD = peak rate of force development; ARFD = average rate of force development.

Table 7. Intercorrelation of force-time variables during the countermovement jump (CMJ).

		CMJ						
		VJD	PF	TPF	PRFD	ARFD	PP	AP
CMJ	VJD	1.00						
	PF	0.51*	1.00					
	TPF	-0.48*	-0.12	1.00				
	PRFD	0.68**	0.64**	-0.46**	1.00			
	ARFD	0.49*	0.63**	-0.44	0.80**	1.00		
	PP	0.73**	0.83**	-0.11	0.60*	0.48*	1.00	
	AP	0.68**	0.86**	-0.22	0.72**	0.73**	0.90**	1.00

CMJ = countermovement jump; VJD = vertical jump displacement; PF = peak force; TPF = time to peak force; PRFD = peak rate of force development; ARFD = average rate of force development; PP = peak power; AP = average power. * denotes significance at $p < 0.05$; ** denotes significance at $p < 0.01$

Table 8. Intercorrelation of force-time variables during the squat jump (SJ).

		SJ					
		PF	TPF	PRFD	ARFD	PP	AP
SJ	PF	1.00					
	TPF	-0.28	1.00				
	PRFD	0.76**	-0.67**	1.00			
	ARFD	0.68**	-0.72**	0.94**	1.00		
	PP	0.73**	0.04	0.48*	0.36	1.00	
	AP	0.82**	-0.40	0.72**	0.67**	0.85**	1.00

SJ = squat jump; PF = peak force; TPF = time to peak force; PRFD = peak rate of force development; ARFD = average rate of force development; PP = peak power; AP = average power. * denotes significance at $p < 0.05$; ** denotes significance at $p < 0.01$

3.4 Discussion

The results of the present study suggest that maximal unloaded VJD measured via the CMJ is primarily determined by PRFD. In the present study, PRFD had a significant correlation (r = 0.68; p = 0.001) to VJD. The present results are in contrast to the results of others (195, 238, 292, 467) which reported poor relationships between PRFD and VJ performance. Wilson et al., (467) found no significant relationship between RFD and dynamic performance of the CMJ and suggested that only concentric tests were a superior testing method for RFD. Haff et al., (195) also found no correlation between RFD and CMJ or SJ in collegiate male and female track athletes. However, methodological differences such as the use of isometric tests to measure PRFD and variations in test methodologies to determine VJD in comparative studies (195, 292, 480) may explain the contrasting results with the results of the present study.

The present study measured VJD while simultaneously measuring PRFD during CMJ and SJ movements on a force plate. The rational for this methodology was to examine the subjects' ability to develop force rapidly during dynamic movement rather than under conditions of isometric force development where a relationship between PF development and its application as an indicator of athletic performance has been challenged (467). Several studies (196, 238) have not used arm swing in their CMJ or calculated VJD by flight time. Methods using flight time to estimate jump height are prone to errors associated with the potential for take off and the landing positions to be inconsistent (243). Accordingly, flight time was not considered to determine VJD for the SJ in the present study.

Arm swing during the CMJ was implemented during the present study from a functional perspective whereby the predominance of sport-specific movements and skills require the arms to be incorporated into dynamic movement and swung vigorously upward during take-off to enhance performance. As such the use of arm movement during the CMJ was considered a more natural movement for subjects to perform. The use of the arms during VJ testing has been reported to increase the skill and coordination requirements of the movement and therefore may lessen the validity of the VJ as a test of lower body musculature (187, 393). Recent evidence suggests that RFD and muscular strength in lower limbs play a greater role in VJ performance than skill, coordination, any motor learning effect or familiarisation procedures (13, 450). Additionally the use of the arms during the VJ has been shown to result in an increase in takeoff velocity when compared to a VJ without arm swing (204, 273). In support of these findings the present study found a significant negative correlation between TPF and VJD (r = -0.48; p = 0.033) during the CMJ (Table 7), highlighting the importance of developing muscular force rapidly during a VJ to attain maximal VJD. The increase in takeoff velocity may, in part, explain why a significant correlation (r = 0.68; p = 0.001) was found between PRFD and VJD

during the CMJ (Table 7) in the present study and not in those studies (204, 273) in which arm swing was not used.

In addition to PRFD, PF was significantly correlated (r = 0.51; $p = 0.023$) to VJD during the CMJ, which suggests that the maximum muscular strength of an individual also contributes to VJD. Petersen et al., (357) found that maximum muscular strength (as measured by one repetition maximum [RM] back squat) was significantly correlated to VJD in college aged athletes. Variability in TPF within an individual however is most likely due changes in neural drive which have a significant influence over force development during the early (0-50 ms) and mid phase (50-200 ms) of increasing muscle force (1). However as the TPF in the present study occurred within 250 ms for both the CMJ and the SJ (Table 4), this would suggest that PRFD rather than maximal strength plays a more significant role in VJD (484). The TPF reported in the present study is similar to some (196) but not others (238) which reported longer times (> 300 ms) to reach PF.

The training status of an individual largely determines the ability to reach PF quickly with explosively trained athletes achieving the fastest TPF (484). The subjects who participated in this study were all physically active but were untrained in explosive exercise, and therefore PRFD exceeded expectations. The results of the present study found poor reliability for PRFD during the CMJ and SJ (Table 5 and 6). The poor reliability of PRFD data during the VJ in the present study is consistent with the work of Moir et al., (313) and is in contrast to previous studies that have used PRFD during the VJ to assess performance (196, 238).

Inconsistency with previous findings (196) may be due to the inclusion of subjects experienced in training with dynamic explosive exercise and the analysis of a single CMJ and SJ trial following two CMJ and VJ warm up trials. The present study included physically active males with no experience in Olympic style lifts or plyometric exercise. The present study used the best of three trials of both the CMJ and SJ for analysis and incorporated arm movement into the CMJ in contrast to the work of Haff et al., (196) who executed all CMJ and SJ trials with hands on hips. Ambiguity also exists with regard to the sequencing of testing and the inclusion of additional test regimes in previous findings (196) that have used PRFD to assess VJ performance. Kawamori et al., (238) included subjects who were experienced weightlifters who were well accustomed to explosive exercise and conducted all CMJ and SJ trials with hands on the hip in contrast to the methodology of the present study. VJD, PF, PP and AP from the CMJ and SJ (Table 5 and 6) in the present study did show a high degree of reliability and are consistent with previous findings (313).

In summary, the present data indicate that there is a significant correlation between VJD and PRFD during the CMJ movement in young, physically active men. The significant correlation between PRFD

and VJD suggests that CMJ performance using the jump and reach method is primarily due to the ability to develop force rapidly (RFD) and to a lesser extent maximal strength (PF). The use of PRFD as a measure of VJ performance when testing males untrained in dynamic explosive exercise techniques however requires caution due to the poor reliability of PRFD and ARFD data.

3.5 Practical Applications

The primary aim of the present study was to examine the relationship between RFD and VJD during the CMJ using a Vertec yardstick measurement device on the basis that access to portable force plates and other portable position transducer equipment is often beyond the reach of sports performance professionals outside of the professional sporting environment. Under these simple field testing conditions, if a positive relationship between VJD and RFD could be determined, scope would exist for athletes, coaches and other sports professionals to consider RFD as a primary determinant of performance in addition to leg power from VJD.

Of the force time variables measured during the CMJ movements in this study, 46.4 % of VJD was determined by PRFD and as such was the largest contributor to VJD in physically active men. This outcome indicates that individuals who produce greater PRFD will have greater VJ performance. Accordingly, training methods emphasizing explosive technique that are designed to improve PRFD should lead to improvements in VJ and ultimately improved dynamic sports performance. In addition to PRFD, PF was found to contribute 25.6 % to VJD during the CMJ therefore maximal strength training designed to develop PF should be included in strength training programs to improve VJ performance. The inclusion of maximal strength training would therefore be appropriate with respect to exercise prescription for untrained or relatively inexperienced individuals where the opportunity to improve maximal strength is greater in comparison to elite athletes who may already be training at or near their genetically predetermined strength capabilities.

The findings of the present study support the inclusion of both explosive type training with minimal loading to improve PRFD and traditional heavy strength training to enhance PF in physically active but inexperienced strength training individuals to improve VJ performance. Researchers and sports professionals should however use caution with respect to the poor reliability of PRFD data to determine VJ performance in untrained individuals.

CHAPTER 4

Performance Analysis of Elite Rugby League Match-Play Using Global Positioning Systems

4.1 Introduction

Rugby League is a collision sport involving frequent bouts of high-intensity exercise (sprinting, tackling, and running) separated by bouts of low-intensity exercise (walking and standing) (159). There is a lack of information regarding the physiological demands and movement patterns of elite Rugby League players during match-play. One way to determine the physiological demands of Rugby League and quantify player movement patterns during match-play is via time-motion analysis incorporating the use of match video recordings performed retrospectively (246, 307, 308, 396).

Meir and colleagues (307, 308) performed retrospective analysis of professional Rugby League match video recordings under the pre-existing 5 m (307) and current 10 m (308) defensive rules. While Meir et al., (307, 308) reported that the majority (84 – 95 %) of match-play consists of low intensity activities such as standing, walking and jogging, the nature of elite Rugby League match-play requires players to perform high intensity activities such as accelerating, directional changes, sprinting and withstanding physical collisions during offensive and defensive phases of play. Early studies (307, 308) of Rugby League match-play were limited by small sample size, the number of positions examined and changes to defensive and interchange rules.

Recent studies (246, 396) have added to our understanding of the physiological demands of professional Rugby League, however no studies have examined player movement patterns under current player interchange rules or the two referee system introduced to the National Rugby League (NRL) in 2009. A greater understanding of the specific demands imposed upon players during match-play is needed to develop Rugby League specific training and recovery programmes, to facilitate optimal on-field performance and reduce the risk of injury.

The limitations of time motion analysis using match video recordings in Rugby League and other football codes have been reported (119, 130). While traditional video tracking methods quantify player movement during competition, the use of varied and inconsistent categories to describe player movement patterns could have compromised our information on the physiological demands and

movement characteristics of match-play in Rugby League. The labor intensive nature of retrospective video recording analysis and the failure to operate in real-time, may make such video analysis prone to measurement error and prolong assessment of player performance indicators (123, 134). As more advanced technologies for performance analysis emerge, there is a need for a concomitant increase in the evaluation and analysis of that information to improve training and recovery practices and reach desired performance outcomes.

Recently, the development of portable Global Positioning System (GPS) units designed for athlete-tracking have provided an alternate data acquisition method to determine the demands of training and competition in real-time (111, 210, 289, 290, 356, 443) with the potential to overcome some of the limitations associated with traditional methods. The GPS is a satellite-based navigation system that permits quantitative measurement of player position, velocity, heart rate (HR) and movement patterns through traditional GPS triangulation methods, accelerometer, and HR monitoring software (134). Investigation of Rugby League match-play incorporating portable GPS units provides scope for a better understanding of the positional specific physiological demands of competition to optimize training outcomes and facilitate on-field performance.

To our knowledge, no study has reported Rugby League match-play movement characteristics using GPS technology. The absence of GPS aquired match-play data in Rugby League may be due to concerns about the accuracy and reliability of portable GPS for high intensity field sports, the size and positioning of the GPS receiver on the player, and the perceived risk of injury associated with the GPS unit during match play (123). Recent advances in GPS technology (390) have increased the accuracy and reliability of the GPS during team sports (134, 289, 290, 356). Furthermore a reduction in the size of the GPS unit has made it less intrusive and can be worn safely during Rugby League match-play.

Uncertainty exists regarding the movement patterns and physiological demands of elite Rugby League match-play under current rule structures, player interchange limits and the introduction of two referees in the NRL. The aim of the present study was to (i) examine the physiological demands elite Rugby League match-play using portable GPS technology to monitor player's movement patterns and heart rate and (ii) examine positional comparisons to determine if a player's physiological requirements are influenced by their playing position during Rugby League match-play. We hypothesize that there will substantial positional differences in movement patterns and exercise to rest ratio activities during elite Rugby League match-play. Further, the utilisation of portable GPS will provide a more detailed and specific analysis of player movement patterns, high intensity and low intensity match-play activities and HR response to the demands of Rugby League match-play than achieved previously.

4.2 Methods

4.2.1 Experimental Approach to the Problem

The GPS technology was used to examine the independent variable of player movement characteristics to determine position specific running profiles during elite Rugby League match-play. To examine the physiological response of the dependent variable during match-play, HR was measured via a portable chest strap HR monitor. GPS and HR data were collected from players during five regular season NRL matches of 80 min duration. All participants played a minimum of 30 min of match-play in each of the two 40 min halves of each match. Players were separated into forwards and backs for positional comparison. An understanding of player movement patterns and HR during match-play is important to monitor performance and effectively plan and manage player preparation for the rigors of competitive match-play.

4.2.2 Subjects

Twenty two elite male Rugby League players, age 24.2 ± 7.3 yrs, height 188 ± 20.1 cm, and mass 94.6 ± 26.8 kg; mean ± SD, representing an NRL team volunteered to participate in the present study. Due to the minimum on field match participation requirements, data were analysed from fifteen players (Forwards n = 8; Backs n = 7) during each match (Total 5 match subjects: Forwards n = 40; Backs n = 35). Prior to the commencement of the study, participants attended a presentation outlining the purpose, benefits and procedures associated with the study. Written informed consent was obtained from all participants. The study was approved by the Bond University Human Research Ethics Committee (BUHREC).

4.2.3 Procedures

4.2.4 Global Positioning System (GPS) Units

The present study used commercially available GPS receivers (SPI-Pro, GPSports, Canberra, Australia) which operated in non-differential mode and provided data in real-time. The SPI-Pro GPS units measure at 5 Hz and contain a tri-axis integrated accelerometer which measures accelerations in gravitational force (G force) on three planes, namely forwards/backwards, up/down and tilt left/right. The GPS model used in the present study (76 g; 48 mm x 20 mm x 87 mm) was worn in a purpose designed vest (GPSports, Australia) to ensure that range of movement of the upper limbs and torso was not restricted. Manufacturer guidelines (GPSports, Canberra, Australia) report the effective

distance of the GPS units used in the present study for data collection as 200 m from the field of play. The GPS unit was worn in a padded mini backpack contained in the vest and positioned in the centre area of the upper back slightly superior to the shoulder blades at approximately the level of the first thoracic vertebrae (T1).

Participants had previously worn GPS units in outdoor training sessions that included Rugby League specific running, skill related and match simulated contact activities during a 16 week pre-season training period. Participants had also worn the GPS units in two pre-season practice games prior to the commencement of the NRL regular season of competition. No participants complained of any discomfort or impediment to their normal range of movement or performance from wearing the equipment during training or competitive match-play. Data provided from the GPS unit included total distance, speed and HR characteristics. Positional data of players wearing GPS units is recorded via comparison of travel time of radio frequency signals emitted from at least four earth orbiting satellites (267). Player speed profile data are determined via measurement of the rate of change in the satellite's signal frequency due to GPS unit movement characteristics (Doppler Shift) (390). Raw accelerometer data were available in real-time via Wireless Fidelity (WiFi) communication and were displayed using commercially available software (Team AMS, GPSports, Australia).

The validity and reliability of GPS and integrated accelerometry to measure distance and speed during high intensity exercise that characterises contact and non-contact sports has been reported (28, 89, 134, 289, 356, 474). The reliability of the SPI-Pro has previously been tested by our laboratory over distances from 5 m to 8000 m on a synthetic 400 m athletics track with variations of < 3 % and the reliability of speed assessed with electronic light gates (Smart-Speed, Fusion Sport, Australia) from walking speed (6 $km \cdot hr^{-1}$) to maximum sprint speed (> 20.1 $km \cdot hr^{-1}$) with variations of < 5.5 %. Our results are similar to others who have reported the reliability of the SPI-Pro GPS (356).

4.2.5 Movement Classification System

A zone classification system forms the basis of the analysis by the Team AMS software, allowing six ranges of speed ($m \cdot sec^{-1}$/ $km \cdot hr^{-1}$) and HR ($b \cdot min^{-1}$) to be set and used for analysis. Zone 1 indicates the lowest effort or lowest velocity of movement with each zone progressively categorizing effort and movement intensity to Zone six which represents the highest effort and intensity of movement. The movement classification system used in the present study was based on methods used in Rugby Union (119) and modified to consider forward, backward and lateral ambulatory movement only. No attempt was made to quantify movement characteristics associated with contact sport specific movements such as tackling, wrestling, jumping and scrimmaging in the present study. The frequency and duration of

entries into each movement zone have been reported to provide a more precise profile of activity patterns among playing position (forwards and backs) in intermittent sports (210).

Each movement zone was coded as one of six speeds of locomotion (Table 9). The movement zone categories were sub-divided into 2 further locomotor categories to provide a crude estimate of player exercise to rest ratios. Standing / walking, and jogging were considered to be low intensity activities (< 12/ km·hr^{-1} / rest), while cruising, striding, high intensity running and sprinting were regarded as high intensity activities (> 12/ km·hr^{-1} / exercise). The duration of each interval of high intensity exercise was divided by the duration of the following rest interval to determine exercise-to-rest-ratio for that passage of play.

4.2.6 Heart Rate

Match HR were recorded from each player by a commercially available HR monitor using chest straps for electrode placement (Polar Electro, Finland). HR signals were transmitted to the GPS unit positioned between the players' shoulder blades. All participants were accustomed to wearing HR chest straps prior to data collection. Participants had worn HR chest straps in outdoor training sessions that included rugby league specific running and game simulated contact activities, during a 16 week pre-season training period. The data were categorized into HR zones using Team AMS software (GPSports, Australia) (Table 10). No participants complained of any discomfort or impediment to their normal range of movement or performance from wearing the HR monitor. Individual maximum HR was recorded as the highest HR achieved during match play.

4.2.7 Statistical Analysis

The statistical software package SPSS version 14.0 was used for the data analysis. Differences in heart rate, running speed and distance travelled between backs and forwards during match-play were determined using Student's unpaired *t*-test. A Student's paired *t*-test was used to determine the differences in heart rate, running speed and distance travelled within the backs and forwards during the first half and second half of match-play. To determine differences in the distance travelled in the different speed zones and the percent time in each heart rate zone, a repeated measures ANOVA was used to compare between backs and forwards for the first and second half and the whole game. Significant differences were located by a Bonferroni *post hoc* test. Significance was accepted when $p < 0.05$. All data are expressed as mean ± SD.

Table 9. Speed zone classification during elite Rugby League match-play using Team AMS software

Zone	km·hr^{-1}	m·sec^{-1}	Movement classification	Definition
1	0 – 6.0	0 – 1.6	Standing / Walking	Standing or walking at low intensity, no flight phase associated with ambulatory movement in any direction.
2	6.1 – 12.0	1.6 – 2.7	Jogging (Low intensity running)	Running in any direction with minimal flight phase and minimal arm swing (1/4 pace).
3	12.1 – 14.0	2.7 – 3.8	Cruising (Moderate intensity running)	Running in any direction with progressive acceleration and elongation of stride length with moderate arm swing (1/2 pace).
4	14.1 – 18.0	3.8 – 5.0	Striding (Medium intensity running)	Running with increased velocity and arm swing (3/4 pace).
5	18.1 – 20.0	5.0 – 5.5	High Intensity Running	Running at near maximum pace (> 85 %) with near maximal stride length, stride frequency and arm swing.
6	> 20.1	> 5.6	Sprinting	Running with maximal effort.

Table 10. Heart rate (HR) zone classification during elite Rugby League match-play using Team AMS software.

Zone	Percentage (%) HR Maximum	HR ($b \cdot min^{-1}$)
1	< 45	40 – 87
2	45.1 – 65.0	88 – 126
3	65.1 – 80.0	127 – 156
4	80.1 – 87.5	157 – 170
5	87.6 – 95.0	171 – 185
6	> 95.1	> 185

4.3 Results

There was no significant difference in the total distance covered during competitive match play between backs (5573 ± 1128 m) and forwards (4982 ± 1185 m) (Table 11). The backs covered more distance at high-intensity running (147 ± 46 m; $p = 0.03$) and sprinting speeds (293 ± 55 m; $p = 0.03$) during the whole match compared to the forwards (80 ± 32 m & 152 ± 28 m respectively) (Table 12). First half analysis revealed no significant difference in the total distance covered between the backs and forwards (Table 11) however backs covered more distance at sprinting speeds (121 ± 28 m; $p = 0.04$) compared to the forwards (73 ± 18 m) (Table 12). Second half analysis found no significant difference in the total distance covered between the backs and forwards. The backs covered more distance at medium intensity running or striding (278 ± 58 m; $p = 0.03$), high-intensity running (91 ± 21 m; $p = 0.005$) and sprinting speeds (185 ± 45 m; $p = 0.03$) compared to the forwards (174 ± 61 m, 41 ± 19 m & 86 ± 23 m respectively) (Table 12).

Table 11. Heart rate (HR), running speed, and distance travelled for forwards and backs during elite Rugby League match-play (5 match analysis).

			Forwards (n = 40)	Backs (n = 35)
Heart Rate ($b \cdot min^{-1}$)	Maximum	First half	199 ± 7	198 ±11
		Second half	197 ± 6	201 ± 9
		Whole game	199 ± 7	201 ± 9
	Average	First half	164 ± 13	161 ± 9
		Second half	167 ± 13	163 ± 10
		Whole game	165 ± 12	162 ± 11
Speed ($m \cdot sec^{-1}$)	Maximum	First half	6.8 ± 0.7	8.5 ± 0.8[a]
		Second half	6.7 ± 0.3	8.6 ± 0.3[a]
		Whole game	6.8 ± 0.5	8.6 ± 0.7[a]
	Average	First half	3.5 ± 1.7	4.1 ± 1.9
		Second half	3.8 ± 1.9	4.6 ± 1.1
		Whole game	3.6 ± 0.9	4.2 ± 1.2
Distance travelled (m)		First half	2685 ± 641	3136 ± 541
		Second half	2553 ± 558	2941 ± 618
		Whole game	4982 ± 1185	5573 ± 1128

Note: [a] significant difference ($p < 0.001$) compared with forwards. Data are mean ± SD.

Backs achieved greater maximum running speed during the first half ($p = 0.001$), second half ($p = 0.0002$) and over the course of the whole match ($p = 0.0002$) compared to the forwards (Table 11). During the first half of each match, backs had a greater total duration of sprinting ($p = 0.03$), had less time between sprints ($p = 0.04$) and covered greater total distance sprinting ($p = 0.03$) than forwards. Similarly in the second half of each match, backs had a greater number of sprints ($p = 0.01$), had less time between sprints ($p = 0.03$), a greater total duration of sprinting ($p = 0.03$) and covered a greater total distance sprinting ($p = 0.01$) than forwards. The whole match speed profile for players from all matches found that backs completed a greater number of sprints ($p = 0.02$) had less time between sprints ($P = 0.02$), covered a greater total duration of sprinting ($p = 0.04$), and achieved a greater total distance sprinting ($p = 0.02$) than forwards (Table 13) during match-play. There was no significant

difference in exercise-to-rest ratios of 1:6 and 1:7 for the backs and forwards respectively, determined from distance covered in each speed zone during the whole match.

Table 12. Distance travelled in different speed zones for forwards and backs during elite Rugby League match-play (5 match analysis).

	Speed ($m \cdot sec^{-1}$)	Forwards Distance (m) (n = 40)	Backs Distance (m) (n = 35)
First Half	0 - 1.6	1127 ± 361	1221 ± 326
	1.6 - 3.3	866 ± 247	887 ± 305
	3.3 - 3.9	182 ± 33	258 ± 64
	3.9 - 5.0	163 ± 37	211 ± 43
	5.0 - 5.6	42 ± 15	56 ± 19
	> 5.6	73 ± 18	121 ± 28[a]
Second Half	0 - 1.6	958 ± 322	1188 ± 231
	1.6 - 3.3	811 ± 305	947 ± 215
	3.3 - 3.9	240 ± 53	263 ± 65
	3.9 - 5.0	174 ± 61	278 ± 58[a]
	5.0 - 5.6	41 ± 19	91 ± 21[a]
	> 5.6	86 ± 23	185 ± 45[a]
Whole Game	0 - 1.6	2126 ± 443	2395 ± 585
	1.6 - 3.3	1727 ± 473	1628 ± 429
	3.3 - 3.9	438 ± 129	426 ± 151
	3.9 - 5.0	373 ± 121	430 ± 174
	5.0 - 5.6	80 ± 32	147 ± 46[a]
	> 5.6	152 ± 28	293 ± 55[a]

Note: [a] significant difference ($p < 0.05$) compared with forwards. Data are mean ± SD.

There was no significant difference in the maximum and average HR achieved during either half of match-play or during the whole match analysis for backs in comparison to forwards (Table 11). Forwards spent a significantly greater percent of time with HR above 170 $b \cdot min^{-1}$ compared to backs during the whole game ($p = 0.02$) and during the first ($p = 0.02$) and second halves ($p = 0.04$) of match-play. Backs spent a significantly greater percent of time with HR below 90 $b \cdot min^{-1}$ compared to

forwards during the whole game ($p = 0.04$) and during the first ($p = 0.03$) and second halves ($p = 0.04$) (Table 14) of match-play.

Table 13. Sprinting (> 5.6 m·sec^{-1}) profile of forwards and backs during elite Rugby League match-play (5 match analysis).

		Forwards (n = 40)	Backs (n = 35)
First Half	Number of sprints (n)	6.2 ± 2.6	7.8 ± 3.7
	Average duration (s)	2.82 ± 0.63	3.11 ± 0.72
	Time between sprints (min)	5.3 ± 2.1	3.2 ± 1.2[a]
	Total duration (s)	12.4 ± 4.3	22.3 ± 4.1[a]
	Total distance (m)	75 ± 21	118 ± 37[a]
Second Half	Number of sprints (n)	5.1 ± 3.2	11.6 ± 3.8[a]
	Average duration (s)	2.71 ± 0.44	2.92 ± 0.51
	Time between sprints (min)	5.8 ± 1.8	3.2 ± 2.2[a]
	Total duration (s)	13.2 ± 3.8	23.9 ± 6.5[a]
	Total distance (m)	85 ± 31	189 ± 47[a]
Whole Game	Number of sprints (n)	11.1 ± 5.1	18.7 ± 6.2[a]
	Average duration (s)	2.88 ± 0.91	3.05 ± 0.87
	Time between sprints (min)	5.2 ± 2.2	3.2 ± 1.1[a]
	Total duration (s)	25.8 ± 9.2	44.7 ± 9.1[a]
	Total distance (m)	153 ± 38	321 ± 74[a]

Note: [a] significant difference ($p < 0.05$) compared with forwards. Data are mean ± SD.

Table 14. Percentage of time spent in different heart rate zones for forwards and backs during elite Rugby League match-play (5 match analysis).

	Heart rate ($b \cdot min^{-1}$)	Forwards (%) (n = 40)	Backs (%) (n = 35)
First Half	< 90	4.2 ± 5.6	10.9 ± 7.7[b]
	90 - 120	6.1 ± 7.2	6.5 ± 5.3
	120 - 150	7.9 ± 9.1	5.1 ± 4.3
	150 - 170	5.7 ± 4.2	10.1 ± 9.9
	> 170	23.2 ± 8.5[a]	10.6 ± 8.7
Second Half	< 90	2.3 ± 2.6	7.1 ± 5.9[b]
	90 - 120	7.0 ± 6.1	6.4 ± 4.6
	120 - 150	6.9 ± 3.6	6.2 ± 4.9
	150 - 170	6.1 ± 3.4	10.3 ± 6.4
	> 170	19.8 ± 7.7[a]	12.1 ± 6.8
Whole Game	< 90	6.6 ± 4.1	19.7 ± 10.8[b]
	90 - 120	16.6 ± 7.7	17.3 ± 11.2
	120 - 150	21.1 ± 7.3	17.9 ± 5.1
	150 - 170	16.8 ± 4.2	25.6 ± 9.3
	> 170	44.5 ± 13.1[a]	22.1 ± 12.4

Notes: [a] significant difference ($p < 0.05$) compared with backs. [b] significant difference ($p < 0.05$) compared with forwards. Data are mean ± SD.

4.4 Discussion

The present study found no significant difference in the total distances covered between backs and forwards in either half of match-play. The total mean distances covered by players in the present study are less than some (307, 308) but similar to recent work that has used match-play video recordings to assess movement patterns in elite Rugby League players (246, 396). The discrepancy with the early studies (307, 308) could in part be due to advancements in match-play analysis technology, defensive rule changes and recent changes to player replacement and interchange rules. Comparison of first and second half running distances indicates that the intensity of match-play was

maintained throughout each match with no deterioration of running ability or physiological fatigue evident amongst all playing positions during match-play.

While there was no significant difference in the total distance covered between backs and forwards during match-play, there were significant differences in the running speeds used to cover the distances recorded from players of those positions. Backs covered greater distances with high intensity running and sprinting compared to forwards in each half and during full match analysis. Similar results have been reported elsewhere with backs spending more time in high intensity activities than forwards (246). The significant difference in high intensity running and maximal sprinting during match-play is most likely due to the requirements of positional play between forwards and backs in Rugby League. Forwards are positioned in close proximity to the centre of play whilst the backs are located in the outer edges and sidelines on either side of the field. The closer proximity of forwards to the centre of play tends to avail players in those positions to run shorter distances (approximately 5 - 12 m (246)) at high speed to perform match specific tasks such as a tackling and ball carrying. Alternatively, backs are often positioned with greater space between themselves and the opposition and therefore cover greater distances to come into contact with an opponent and have the added task of sprinting to perform kick return and kick chase activities (246).

Our finding that backs travelled further at higher speeds in comparison to forwards throughout each match is consistent with the findings of others (246) and is influenced by greater opportunity to achieve high-intensity and sprinting speeds by backs. The majority of match-play for both positional groups was spent performing low-intensity activities. Our findings are consistent with others who have reported a predominance of low-intensity activity during Rugby League match-play (246, 307, 308) and support the implementation of Rugby League specific training programs that involve repeated high-intensity exercise interspersed with periods of low-intensity activity to prepare players for the demands of match-play.

In support of research (78) that examined the speed characteristics of elite Rugby League players, and found backs to be consistently faster than forwards over 40 m, and others (159) that have investigated the maximum running speed of Rugby League players, backs achieved faster running speeds during competitive match-play in comparison to forwards in the present study. Backs completed a greater number of sprints (running speed > 5.6 $m \cdot sec^{-1}$) during the match (19 ± 6 vs 11 ± 5 respectively) , backs also sprinted for a greater total duration (44.7 ± 9.1 s vs 25.8 ± 9.2 s), and covered greater distances at maximum speed (321 ± 74 m vs 153 ± 38 m) compared to forwards. Overall, the data indicate that backs participate in a greater amount of higher intensity activity when compared with forwards and is consistent with the results of others (111, 396).

There was no significant difference in the average sprint duration during each match between backs and forwards in the present study (3.05 ± 0.87 s and 2.88 ± 0.91 s respectively). These values are similar to the average sprint duration reported from rugby union forwards and backs and equates to sprinting distances of approximately 20 - 30 m (119) and implies that the ability to accelerate rapidly is highly important in elite Rugby League match-play. While these data represent average sprint durations, players are regularly required to sprint distances greater than 30 m (396). Time between sprints was higher than expected with forwards displaying significantly longer periods between sprint efforts in both halves and during the whole match compared to backs. The prolonged periods separating sprint efforts seen in forwards may be due to players in these positions regularly running distances that are insufficient to achieve maximal sprinting velocity (< 15 - 20 m) in comparison to backs. The varied sprint profiles identified in the present study for forwards and backs supports the need for positional specificity in speed training for elite rugby league match-play.

The exercise-to-rest ratios determined from distance covered in each speed zone during match-play was 1:6 and 1:7 for the backs and forwards respectively. These values are lower than earlier reports (307) but similar to values reported in recent studies (246). The discrepancy between our results and others may in part be due to the classification of positional groups, player ability and fitness levels and differences in the methods used to assess movement during match-play. Although exercise-to-rest ratios provide important information on match-play demands, exercise-to-rest ratio data calculated from player activity may underestimate actual exercise time and as such, data obtained from contact based team sports must be viewed with some caution. Ratios of 1:6 and 1:7 indicate that players are not required to perform repeated high-intensity efforts (< 1:2 exercise-to-work ratio) and receive substantial opportunity for rest during low-intensity activity between high-intensity exercise efforts. The results of the present study however are representative of the total distance covered during the match and do not reflect periods of play that may involve repeated or continuous periods of high-intensity exercise (409). Our results are based on the speed associated with match-play activity and do not consider substantial time spent participating in Rugby League specific pushing, pulling, wrestling and scrums that register as low-intensity activity using GPS technology despite intense exercise being performed in a stationary position. The exercise-to-rest ratio provides information on the intermittent nature of Rugby League running, however the exercise-to-rest ratio based on running speeds may not be a true reflection of actual exercise rates during match-play. Nevertheless the exercise-to-rest ratios in the present study and other research (246, 396) indicate that most of the energy required to perform the periods of high-intensity activity is derived from the ATP-PC system and anaerobic glycolysis (178).

There was no significant difference in the maximum and average HR achieved during competition between the backs and forwards. The average HR of the players in the present study is approximately

equal to players averaging over 70 % of their maximum oxygen consumption (VO_2 max) for the duration of match-play. The present results indicate that the metabolic demands of elite Rugby League are high. Esposito et al., (143) and others (27) have suggested that HR values can be converted to VO_2 using the relationship between HR and VO_2 obtained during treadmill running. While elevations in HR may over-predict aerobic demand during high-intensity exercise (372) the measurement of HR has been shown to be a valid and reliable method of determining the intensity and physiological demands during team sports (143) and an appropriate index of overall physiological strain during Rugby League match-play (92).

Although there was no significant difference in the average HR between backs and forwards in either half of match-play or during each whole match, analysis of the time spent in each HR zone reveals that forwards spend a larger percent of time in both halves and during the whole match with HR > 170 $b \cdot min^{-1}$. This equates to over 85 % of maximum HR and is consistent with previous research (92). The average HR for players in the present study are also similar to values reported for sub-elite Rugby League players (92) and support the traditionally held view that there is a large aerobic component required for the performance of competitive Rugby League (307, 308).

Our finding that there was no significant difference in the distance covered by backs and forwards during match-play yet there was the greater amount of time spent in the higher HR zone suggests that the forwards were engaged in high-intensity activity other than running during match-play, a view supported by King et al., (246). Upper body exercise such as tackling, wrestling and scrimmaging which involve the upper body musculature and have been shown to produce higher HR and physiological strain compared to lower body activities performed at similar intensities (441). Backs spent significantly more time with HR below 90 $b \cdot min^{-1}$ during each first half period and during each whole match compared to forwards. The greater amount of time with a HR below 90 $b \cdot min^{-1}$ is most likely due to the nature of the positional play of backs whereby more time is spent standing/walking in the defensive and offensive line compared with forwards that are predominantly involved with moving the ball in the middle of the playing field (246). Our results indicate that forwards might need a higher VO_2 max than backs to meet the competitive demands of elite Rugby League.

4.5 Practical Applications

A better understanding of the demands of elite Rugby League match-play is required to improve the analysis of individual performance characteristics and implement a systematic approach to the development of position specific training programs. Our results indicate that elite Rugby League players are required to complete frequent bouts of high-intensity activity separated by short bouts of

low-intensity activity. Considerable difference exists between the physiological and movement demands of forwards and backs during competitive match-play in Rugby League, especially in the frequency, duration and distances associated with high-intensity locomotor activity. Simultaneous measurement of HR and movement patterns during match-play revealed positional variation in the physiological demand of competition. Our results support the requirement of a high aerobic capacity for elite rugby league players, particularly for forwards who spend > 50 % of match-play performing activities at > 85 % HR_{max}.

Due to the large component of match-play spent performing non-locomotor high-intensity activities such as pulling, pushing and tackling, a combination of GPS-accelerometer analysis technology and match video recordings may provide greater insight into the determination and categorization of impact forces/accelerations received/exerted during the frequent and varied contact elements of elite Rugby League match-play. Further establishment of these collision based variables and their influence on performance, fatigue and recovery will permit appropriate training and recovery protocols to be established to optimize performance.

CHAPTER 5

Creatine Kinase and Endocrine Responses of Elite Players Pre, During and Post Rugby League Match-Play.

5.1 Introduction

Rugby League is a heavy contact sport played internationally and involves frequent bouts of high intensity exercise separated by bouts of low intensity exercise during match-play (169). Traditionally, movement patterns associated with rugby league match-play have been examined using time-motion analysis systems incorporating match video recordings (307, 308). Varied and inconsistent categories to describe locomotor activity however, increase the likelihood of error given the complex and varied nature of Rugby League match-play. Furthermore, the labor intensive nature of video-based analysis systems and an inability of these systems to operate in real time may delay and add to error in match-play analysis (123, 134).

Recent studies (246, 396) have added to our understanding of the performance characteristics of professional Rugby League match-play. Advances in performance analysis technologies, such as Global Positioning Systems (GPS) permit real-time quantitative assessment of the physiological demands of match-play and player movement patterns (89, 289). The validity and reliability of GPS for assessing movement patterns in field-based sports have been reported (134, 289, 356, 362); however, there are few data to identify the validity and reliability of GPS devices to measure intermittent high-intensity exercise that is characteristic of Rugby League match-play (89). As more advanced technologies for performance analysis emerge, there is a need for a concomitant increase in match-play analysis methodologies to increase our understanding of the applied physiology of performance and to improve training practices to achieve desired performance outcomes.

The combative nature of Rugby League match-play combined with intermittent high-intensity activity during competition is synonymous with repeated blunt force trauma, micro-damage to skeletal muscle and post-exercise muscle soreness. Exercise induced muscle damage (EIMD) has been examined in humans (132, 216) with plasma CK concentration ([CK]) commonly reported as an indirect marker of skeletal muscle damage (355, 426). Elevated plasma [CK] has been reported following competitive match-play in contact sports (259, 424, 426) suggesting significant skeletal muscle damage occurs

during such contact sports. Takarada (426) reported a significant correlation between the number of tackles performed during Rugby Union match-play with peak [CK] measured 24 hr post match. The CK and endocrine response to competitive Rugby League match-play however is unknown.

The examination of endocrine measures in response to competitive contact sport performance (86, 137, 216, 259) and during the post competition recovery period (137, 259) are common practice in professional sports. Testosterone and cortisol have been identified as reliable markers of the endocrine response to competitive contact sport performance (86, 137, 353). Testosterone is the primary anabolic marker for protein signaling (410) and muscle glycogen synthesis (218). Cortisol is considered an important stress hormone, and acts antagonistically with testosterone to mediate catabolic activity, increasing protein degradation and decreasing protein synthesis in muscle cells (258). It is possible that various hormonal and muscle enzyme measures may assist in assessing the immediate response and time course of recovery following competition.

The use of salivary testosterone concentration ([sTest]) and salivary cortisol concentration ([sCort]) assay measures constitute relatively simple, non-invasive procedures that provide a valid and reliable indication of plasma unbound cortisol (65, 456) and plasma free testosterone (462). Testosterone and Cortisol have been reported to vary in opposite directions in response to exercise, producing a decreased salivary T:C (sT:C) ratio when training and competitive demands are increased (137, 218). Consequently, T:C ratio has been used to examine the anabolic:catabolic endocrine profile of athletes from contact sports (86, 137). However, the response of testosterone and cortisol to competitive Rugby League match-play is unreported. A better understanding of the endocrine response to competitive Rugby League match-play and the short term post-match recovery period may provide scope for improved individualized training and recovery strategies.

Uncertainty remains regarding the pattern of CK and endocrine responses to elite level contact sport, and the influence of an elite Rugby League match is unknown. It also remains unclear whether the incorporation of such measures is of use to monitor performance in an applied sports setting. The aim of the present study therefore is to 1) examine player movement patterns to determine total distance covered during competitve Rugby League match play using GPS and 2) examine pre, during and post-match CK and endocrine responses to competitive Rugby League match-play. We hypothesize that Rugby League match-play will result in substantial skeletal muscle damage and considerable elevation in stress hormone levels post-match. Further, the combination of GPS performance data with CK, sCort and sTest provides a more detailed and specific analysis of the demands of Rugby League match-play than achieved previously.

5.2 Methods

5.2.1 Experimental Approach to the Problem

GPS technology was used to examine the independent variable of player movement characteristics to determine positional running profiles during elite Rugby League match-play. Plasma CK activity was examined to reflect skeletal muscle damage in response to the demands of match-play. Cortisol and testosterone were examined to represent the primary catabolic and anabolic endocrine measures associated with metabolism and protein synthesis respectively pre- and post-match. To examine the acute and short term post-match response of the dependent variables, sCort, sTest and [CK] were measured via saliva and blood samples respectively. The ratio of salivary testosterone to cortisol (sT:C) was examined to identify the balance between anabolic and catabolic metabolism. An understanding of player movement characteristics, endocrine responses and skeletal muscle damage markers following competitive Rugby League match-play is important to monitor recovery and effectively manage the pre-match training and preparation process for subsequent matches.

5.2.2 Subjects

Seventeen elite male Rugby League players, age 24.2 ± 7.3yrs, height 188 ± 20.1cm, and mass 94.6 ± 26.8 kg, representing a NRL team volunteered to participate in the study. Data were collected during a single game of Rugby League with all participants completing a minimum of 30 min of match-play in each of the two 40 min halves of the match. Prior to the commencement of the study, participants attended a presentation outlining the purpose, benefits and procedures associated with the study. Written informed consent was obtained from all participants. The study was approved by the Bond University Human Research Ethics Committee (BUHREC).

5.2.3 Procedures

Saliva and blood samples were collected 24 hr pre-match, 30 min pre-match, within 30 min post-match and at 24 hr, 48 hr, 72 hr, 96 hr and 120 hr post-match. The saliva and blood collection schedule is outlined in Table 15. Subjects were asked to refrain from strenuous exercise during the 24 hr prior to baseline saliva and blood sample collection (24 hr pre-match). Saliva and blood samples were collected daily between 1530 hr and 1630 hr with the exception of the 30 min post-match saliva and blood samples that were collected between 1830 hr and 1900 hr due to the time of match play. Players provided saliva and blood samples within 30min of match completion and prior to

participation in post-match team recovery activities. Throughout the post-match data collection period (30 min post-match to 120 hr post-match) all subjects participated in all team recovery and training sessions (Table 16). An example of a training week during a 6 week pre-season phase is outlined in Table 17.

5.2.4 Global Positioning System (GPS) Analysis

The present study used commercially available 5 Hz GPS receivers (SPI-Pro, GPSports, Canberra, Australia) which operated in non-differential mode and provided data in real time. The SPI-Pro units (GPSports, Australia) contain a tri-axis accelerometer which measures accelerations in gravitational force (G force) in three planes, namely forwards-backwards, up-down and tilt left-right. The GPS model used in the current study (70 g; 45 mm x 90 mm x 34 mm) was worn in a purpose designed vest (GPSports, Australia) to ensure that range of movement of the upper limbs was not restricted. The GPS unit was worn in a padded mini backpack in the rear of the vest and positioned in the centre of the upper back slightly superior to the shoulder blades at the level of approximately the first thoracic vertebrae (T1).

Subjects had worn GPS units during outdoor training sessions that included Rugby League specific running, skill related and match simulated contact activities. None of the players complained of any discomfort or impediment to their normal range of movement or performance from wearing the equipment during training or match participation. Data provided from the GPS units included total distance and speed characteristics. Raw accelerometer data were available in real time via Wireless Fidelity (WiFi) communication and were displayed using commercially available software (Team AMS, GPSports, Australia). The reliability of the GPS units used in the present study have previously been tested in our laboratory over distances of 10 m to 8000 m on a synthetic 400 m athletics track with variation < 3 % and the reliability of speed assessed with electronic timing gates (Smartspeed, Australia) from walking speed (6 $km.hr^{-1}$) to a maximum sprint speed (> 23.1 $km.hr^{-1}$) with variation < 5.5 %. Our results are similar to others who have reported the reliability of the SPI-Pro GPS units (356).

Table 15. Saliva and blood sample collection schedule 24 hr pre-match to 120 hr post-match.

Day	1	2 & 3	4	5	6	7	8
Sample	Pre Game	Game Day	←		Post Game		→
Time	24hr	Pre/Post Match	24 hr	48 hr	72 hr	96 hr	120 hr
Sample	Saliva	Saliva (pre & post)	Samples collected every 24 hr for the next 5 days				
	Blood	Blood (pre & post)	Samples collected every 24 hr for the next 5 days				

Table 16. Saliva and blood sample collection and training schedule 24 hr pre to 120 hr post-match.

Day	1	2	3	4	5	6	7
Sample	24 Pre	Game Day Pre & Post	24 hr Post	48 hr Post	72 hr Post	96 hr Post	120 hr Post
AM	Off	Off	Recovery 1	Off	Off	Off	Off
PM	Team Training	Game	Recovery 2	Strength	Team Skills	Strength	Team Skills

5.2.5 Movement classification system

Movement zones form the basis of the analysis performed by the Team AMS software, allowing 6 ranges of speed ($km.hr^{-1}$ and $m.s^{-1}$) to be set and used for analysis. Zone 1 indicates the lowest effort or lowest velocity of movement, with each zone progressively categorizing effort and movement intensity to zone 6 representing the highest effort and intensity of movement. The movement classification system used in the present study was based on methods reported elsewhere (119) and modified to consider forward, backward and lateral ambulatory movements. No attempt was made to quantify movement characteristics associated with contact sport specific movements such as tackling, wrestling, jumping and scrimmaging in the present study. Each movement was coded as one of six speeds of locomotion (Table 18) with the frequency and duration of entries into each movement zone providing a more precise profile of activity patterns among playing position during competitive match play.

5.2.6 Plasma Creatine Kinase Sampling and Analysis

Plasma CK concentration ([CK]) was determined from 30 µl capillarized whole blood samples collected via fingertip puncture made using a spring-loaded single use disposable lancet. Blood samples were collected from subjects simultaneously at the time of saliva sample collection (Table 15). Whole blood samples were centrifuged (Heraeus, Function Line) at 3000 rpm for 10 min, separated plasma was stored at a temperature of -30 °C until analysis. Plasma samples were analysed using a Reflotron spectrophotometer (Abbott Architect) via an optimised UV-test.

5.2.7 Salivary Testosterone and Cortisol Sampling and Analysis

Unstimulated saliva was collected via passive drool into a plastic tube for analysis of [sTest], [sCort] and used in the subsequent calculation of sT:C ratio. Saliva measures of [sTest] and [sCort] are independent of salivary flow rate (367). There is a strong relationship between saliva and serum unbound cortisol concentration ($r = 0.87$), salivary free testosterone and serum testosterone ($r = 0.96$) and the sT:C ratio in saliva is highly correlated with that in serum ($r = 0.83$) (342). All subjects were requested to avoid the ingestion of food and fluids other than water in the 60 min before providing each saliva sample, and refrain from brushing their teeth 2 hr prior to each saliva sample collection session. Subjects were instructed to wait for a period of 10 min following their last consumption of

water before commencing the saliva sample collection process. Saliva samples were stored at a temperature of – 80 °C until analysis.

Saliva Cortisol ($\mu g \cdot dL^{-1}$) and Testosterone ($pg \cdot mL^{-1}$) were analysed in duplicate via a commercially available enzyme-linked immunosorbent assay (Salimetrics, PA, USA) using a microplate reader (SpectraMax 190, Molecular Devices, CA, USA). Standard curves were constructed as per the manufacturer's instructions and commercially available standards and quality control samples were used for both assays (Salimetrics LLC). Assay sensitivity was 3.70 $pg \cdot mL^{-1}$ for sTest with intra-assay coefficient of variation (CV) of 5.9 %. Cortisol sensitivity was 0.007 $ng \cdot mL^{-1}$ with an average intra-assay CV of 2.6 %. All samples were analysed in the same series in order to avoid inter-assay variability. The T:C ratio was determined by dividing the concentration of sCort by the concentration of sTest at each 24 hr saliva sample collection period.

5.2.8 Statistical Analysis

Endocrine and muscle enzyme variables analysed pre-match and post-match included sTest, sCort and plasma CK. Prior to statistical analysis, log transformation was applied to the endocrine data to normalize the distribution and reduce non-uniformity bias. The data for each of the dependent variables are represented as mean (± *SEM*) using standard statistical methodology. Changes in hormonal concentrations were analysed using a one-way repeated measures ANOVA. Significant differences were identified via a Bonferroni post hoc test. The criterion level for statistical significance was set at $p \leq 0.05$. The correlation between peak changes in endocrine measures and GPS variables was analysed using the Pearson product-moment correlation coefficient. The mean coefficient of variation (CV) for CK assays was 6.1 %. All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS for Windows, version 14.0; SPSS, Inc., Chicago, IL).

Table 17. An example of training week during a 6-week pre-season phase in professional Rugby League.

Session	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
AM	Team Training (Wrestle) 60-90 min	* Resistance Training 2 UB Strength & Power 60 min 10-15 sets 4-8 RM	Speed Training 45-60 min 100 Club 45-60 min	Team Training (Conditioning) 60-90 min	* Resistance Training 3 UB Push / Pull 60 min 10-15 sets 6-8RM	* Resistance Training 4 LB / UB Push 60 min 10-15 sets 6-8RM	Active Rest
PM	* Resistance Training 1 LB Strength & Power / UB Push 60 min 10-15 sets 4-8 RM	Team Training (Skills) / Recovery 60-90 min	Active Rest	Cross Training 45-60 min	Team Training (Skills) / Recovery 60-90 min	Active Rest	Active Rest

* Resistance training – typical exercises were as follows: Strength exercises: squat variation, vertical push, vertical pull, horizontal push, horizontal pull. Power exercises: bench throw, squat jump, power clean, push press variations. Team training (Wrestle): Individual / partner attack and defence tackling and ruck play drills. Team Training (Skills): Attack and defensive patterns, game plans and general skills. Recovery: Pool deep water running (15 min), general stretching (20 min) and cold water immersion (10 min), massage (30 min). Speed Training: Agility / footwork and reaction drills for 10 min, straight line and change of direction sprints 5-50 m x 4-8 reps, resisted (towing, weighted sled, up hill sprints) / assisted (overspeed bungees, catapault sprints, down hill sprints) 10-40 m x 4-8 reps, plyometric drills (bounding, repeated horizontal jumps, repeated hurdle jumps). Team Training (Conditioning): Aerobic and anaerobic conditioning activities, repeated high-intensity running efforts. 100 Club: additional aerobic and anaerobic conditioning for nominated players. Cross Training: Boxing, Squash, Water Polo, Beach Volleyball, Surfing, Kayaking, Outriggers. Reps = repetitions; 1RM = 1 repetition maximum, UB = Upper body, LB = Lower body

Table 18. Speed zone classification using Team AMS software.

Zone	km·hr^{-1}	m·sec^{-1}	Movement classification	Definition
1	0 – 6.0	0 – 1.6	Standing / Walking	Standing or walking at low intensity, no flight phase associated with ambulatory movement in any direction.
2	6.1 – 12.0	1.6 – 2.7	Jogging (Low intensity running)	Running in any direction with minimal flight phase and minimal arm swing (1/4 pace).
3	12.1 – 14.0	2.7 – 3.8	Cruising (Moderate intensity running)	Running in any direction with progressive acceleration and elongation of stride length with moderate arm swing (1/2 pace).
4	14.1 – 18.0	3.8 – 5.0	Striding (Medium intensity running)	Running with increased velocity and arm swing (3/4 pace).
5	18.1 – 20.0	5.0 – 5.5	High Intensity Running	Running at near maximum pace (> 85 %) with near maximum stride length, stride frequency and arm swing.
6	> 20.1	> 5.6	Sprinting	Running with maximum effort.

5.3 Results

GPS Movement analysis

There was no significant difference in the total distance travelled during the match between backs (5747 ± 1095 m) and forwards (4774 ± 1186 m) (Table 19). Backs travelled greater distance at high-intensity running (5.0 – 5.5 m.s $^{-1}$) (135 ± 49 m; $p < 0.05$) and sprinting (> 5 .6 m.s $^{-1}$) (290 ± 69 m; $p < 0.05$) compared to the forwards (82 ± 21 m & 149 ± 32 m respectively) (Table 20) during the whole match. In the first half there was no significant difference in the total distance travelled between the backs and forwards (Table 19); however backs travelled greater distance at sprinting speeds (110 ± 32 m; $p < 0.05$) compared to the forwards (68 ± 13 m) (Table 20). In the second half there was no significant difference in the total distance travelled between the backs and forwards. The backs travelled greater distance at moderate intensity running (267 ± 68 m; $p < 0.05$), high-intensity running (87 ± 30 m; $p < 0.05$) and sprinting speeds (177 ± 38 m; $p < 0.05$) compared to the forwards (168 ± 56 m, 39 ± 13 m & 82 ± 14 m respectively) (Table 20).

Table 19. Running speed, and distance travelled for the first half, second half and whole match for forwards and backs.

			Forwards (n = 8)	Backs (n = 7)
Speed (m·sec^{-1})	Maximum	First half	6.8 ± 0.3	7.5 ± 0.8[a]
		Second half	6.7 ± 0.1	8.6 ± 0.1[a]
		Whole game	6.8 ± 0.3	8.6 ± 0.1[a]
	Average	First half	2.9 ± 0.9	3.4 ± 1.7
		Second half	3.8 ± 1.4	4.8 ± 0.6
		Whole game	3.2 ± 0.8	3.9 ± 1.0
Average distance travelled (m)		First half	2367 ± 620	3095 ± 510
		Second half	2463 ± 570	2936 ± 573
		Whole game	4774 ± 1186	5747 ± 1095

Note: [a] significant difference ($p < 0.05$) compared with forwards.

Creatine Kinase.

Plasma [CK] measured from 24 hr pre-match to 120 hr post-match are displayed in Figure 6. Plasma [CK] was not significantly correlated ($p > 0.05$) with total distance travelled ($r = 0.28$) during the match. In comparison to 30 min pre-match, a significant increase in [CK] was established immediately post-match ($p < 0.05$) with a further significant increase and peak measure at 24 hr post-match ($p < 0.05$). Substantial increases in [CK] were identified immediately post-match (+ 56 %) and 24 hr post-match (+ 91 %) with progressive decreases in [CK] from 48 hr post-match (- 32 %), 72 hr post-match (- 3 %), 96 hr post-match (-18 %) and 120 hr post-match (- 12 %). In comparison to 24 hr pre-match significant increases in [CK] were identified at all subsequent sample collection points. Despite 120 hr of recovery post-match, plasma CK did not return to 24 hr pre-match baseline levels.

Table 20. Distance travelled in different speed zones for the first and second half and whole match for forwards and backs.

	Speed ($m \cdot sec^{-1}$)	Forwards (m) (n = 8)	Backs (m) (n = 7)
First Half	0 -1.6	1037 ± 378	1200 ± 379
	1.6 - 3.3	841 ± 258	870 ± 272
	3.3 - 3.9	156 ± 49	263 ± 77
	3.9 - 5.0	158 ± 54	195 ± 59
	5.0 - 5.6	35 ± 12	57 ± 21
	> 5.6	68 ± 13	110 ± 32[a]
Second Half	0 -1.6	923 ± 338	1195 ± 263
	1.6 - 3.3	804 ± 287	930 ± 265
	3.3 - 3.9	230 ± 70	244 ± 76
	3.9 - 5.0	168 ± 56	267 ± 68[a]
	5.0 - 5.6	39 ± 13	87 ± 30[a]
	> 5.6	82 ± 14	177 ± 38[a]
Whole Game	0 -1.6	2021 ± 496	2407 ± 541
	1.6 - 3.3	1739 ± 456	1605 ± 424
	3.3 - 3.9	419 ± 115	410 ± 134
	3.9 - 5.0	368 ± 101	440 ± 145
	5.0 - 5.6	82 ± 21	135 ± 49[a]
	> 5.6	149 ± 32	290 ± 69[a]

Note: [a] significant difference ($p < 0.05$) compared with forwards.

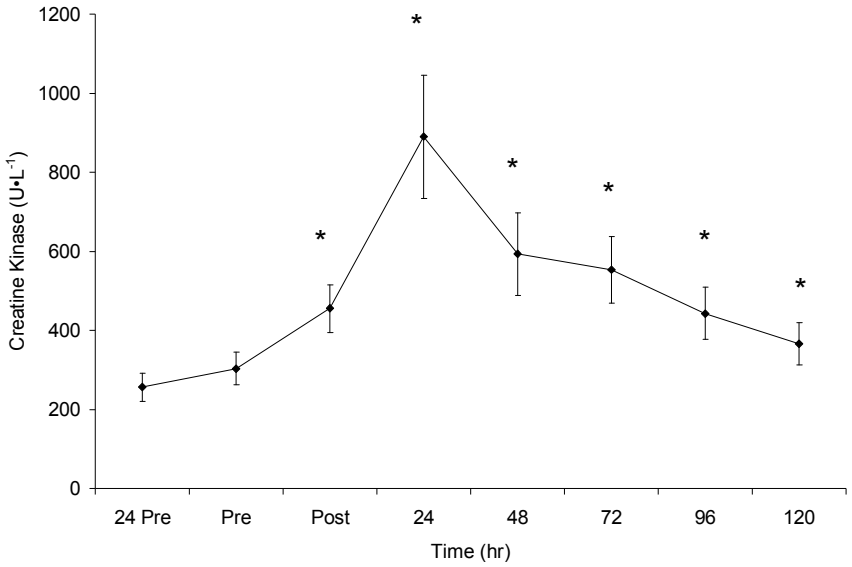


Figure 6. Serum creatine kinase (CK) concentration pre and post Rugby League match-play. All data log transformed and are reported as mean ± SEM. * Significantly ($p < 0.05$) different from 24 hr pre-match.

Cortisol

No significant correlation ($p > 0.05$) was found for sCort and sTest and total distance travelled (r = 0.09 & r = - 0.07 respectively) during match-play. The [sCort] response from 24 hr pre-match to 120 hr post-match is shown in Figure 7. Prior to the start of the match, a significant increase ($p < 0.05$; + 28 %) in [sCort] was found between 24 hr pre-match and 30 min pre-match. The [sCort] continued to increase significantly ($p < 0.05$; + 68 %) from 30 min pre-match to 30 min post-match resulting in the peak [sCort]. A significant decrease in [sCort] was found at 24 hr post-match ($p < 0.01$; - 32 %). A return of [sCort] to baseline measures was evident 48 hr post-match (- 37 %) which remained below baseline measures for the remainder of the study.

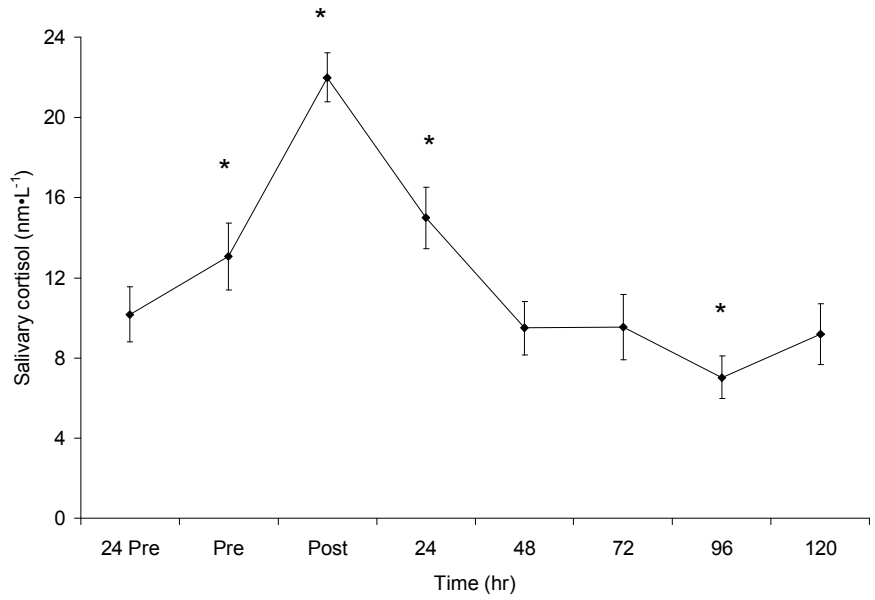


Figure 7. Saliva cortisol concentration pre- and post Rugby League match-play. All data log transformed and are reported as mean ± SEM. * Significantly ($p < 0.05$) different from 24 hr pre-match.

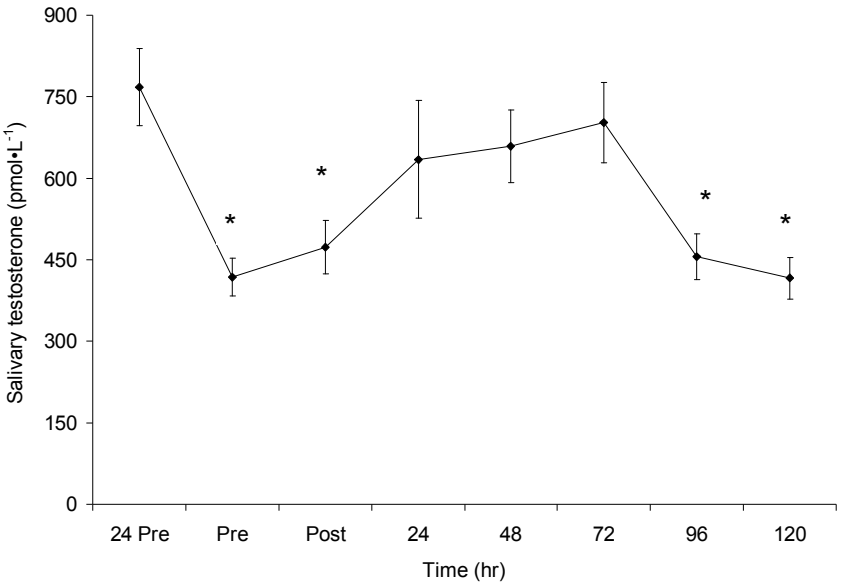


Figure 8. Saliva testosterone concentration pre- and post Rugby League match-play. All data log transformed and are reported as mean ± SEM. * Significantly ($p < 0.05$) different from 24 hr pre-match.

Testosterone

The [sTest] response to competitive match-play can be found in Figure 8. There was a significant decrease in [sTest] from 24 hr pre-match to 30 min pre-match ($p < 0.01$; - 47 %). Despite a small increase (+ 14 %) in [sTest] 30 min post-match, [sTest] remained significantly reduced ($p < 0.05$) in comparison to 24 hr pre-match. The [sTest] increased (+ 33 %) 24 hr post-match resulting in a return to the 24 hr pre-match baseline measures. There was a significant decrease in [sTest] following 96 hr ($p < 0.05$; - 29.35 %) and 120 hr ($p < 0.05$; - 7.56 %) of recovery, returning [sTest] concentration to below 24 hr pre-match levels.

Testosterone:Cortisol Ratio

The sT:C ratio from 24 hr pre-match to 120 hr post-match are shown in Figure 9. A significant decrease in sT:C ratio was found from 24 hr pre-match to 30 min pre-match ($p < 0.05$; - 58 %) followed by a further decrease 30 min post-match ($p < 0.05$; - 33 %). During the acute recovery phase, despite an increase (+ 97 %), T:C remained significantly reduced ($p < 0.05$) 24 hr post-match in comparison to 24 hr pre-match baseline measures. A substantial, though not significant increase in sT:C (+ 64 %) was recorded at 48 hr post-match, returning sT:C to 24 hr pre-match levels. Following 120 hr of the short term recovery phase, T:C ratio decreased ($p < 0.05$) significantly in comparison to 24 hr pre-match baseline measures.

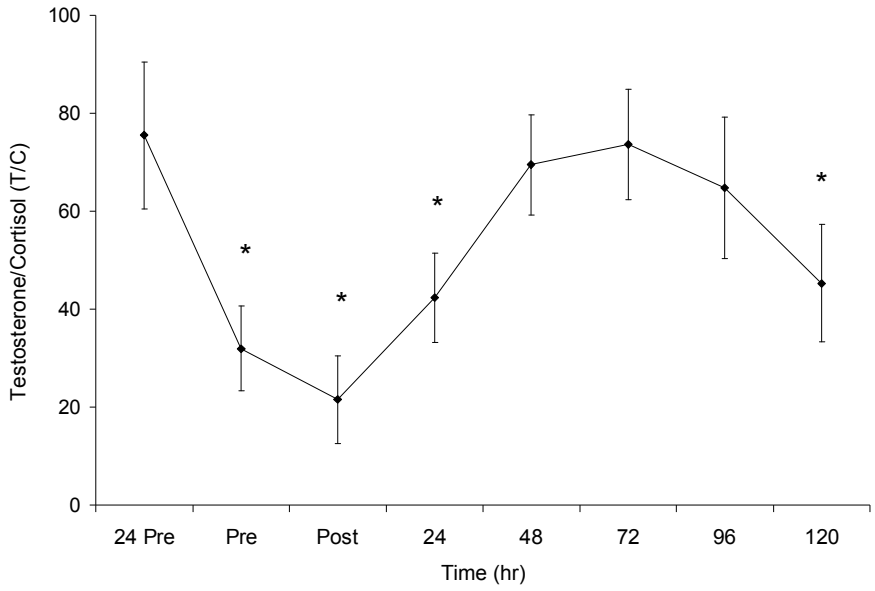


Figure 9. Testosterone:cortisol (T:C) ratio pre- and post Rugby League match-play.

* Significantly ($p< 0.05$) different from 24 hr pre-match.

5.4 Discussion

The primary findings of the present study are that participation in competitive Rugby League match-play results in a significant increase in muscle damage post-match, indicated by elevated [CK] that peaks within 24 hr post match and remained elevated in comparison to pre-match values, for at least 120 hr following competition. An anticipatory rise in the concentration of sCort was found prior to match-play followed by an acute and considerable increase in [sCort] immediately post-match. The [sCort] was found to peak immediately post-match followed by a return to resting concentrations within 24 - 48 hr post-match. Conversely, a reduction in [sTest] was found pre-match followed by an acute post-match increase that progressively returned to baseline concentration within 24 hr post-match.

The present study found no significant difference in the total distance travelled between backs and forwards in either half of match-play or over the full match. The total full-match mean distances reported for backs and forwards were 5747 ± 1095 m and 4774 ± 1186 m respectively. The maximum distances travelled by players in the present study are similar to the distances reported by others (246, 396) using match video recordings to analyse movement characteristics in Rugby League match-play. The similarity of distances covered between backs and forwards and the consistency of running characteristics in each half of the match indicate match intensity was maintained and the characteristics of running performance did not deteriorate during the whole match. Further, similarity in the distances recorded by GPS and video analysis methods suggest GPS may be a useful alternative to the measurement of distances travelled by players during competitive match-play in Rugby League.

In the present study significant differences in the running speeds used to cover the total distances travelled during match-play were recorded between forwards and backs. In the first half, backs travelled significantly greater distance during maximal sprinting in comparison to forwards (110 ± 32 m and 68 ± 13 m respectively). During the second half, backs travelled significantly greater distance during striding (267 ± 68 m), high intensity running (87 ± 30 m) and maximal sprinting (177 ± 38 m) in comparison to forwards (168 ± 56 m; 39 ± 13 m; and 82 ± 14 m respectively). Subsequently, on the basis of whole match performance, backs travelled significantly greater distance during high intensity running and sprinting (135 ± 49 m; 290 ± 69 m) compared to forwards (82 ± 21 m; 149 ± 32 m). To our knowledge, no previous studies have quantified distances travelled by players according to speed profile characteristics and playing position during Rugby League match-play.

The significant positional differences in striding, high intensity running and sprinting during match-play is reflective of the fundamental characteristics of positional play in Rugby League. Forwards are positioned in close proximity to the centre of play, requiring those players to run shorter distances at

high speed to perform game specific tasks. Alternatively, backs are often positioned a greater distance from their opponent and therefore are required to travel greater distances at higher speeds (169) thereby providing greater ability to achieve higher velocity running. Backs have the additional tasks of sprinting into position over greater distances to perform kick return and kick chase activities thereby increasing their opportunity to achieve maximum sprint velocities. Overall, the data indicates that backs participate in a greater amount of high intensity locomotor activity over similar total distances in comparison to forwards during match-play.

Although eccentric muscular work has traditionally been considered the predominant contributor to increased [CK] after exercise (57) recent evidence suggests that significant increases in plasma [CK] may occur as a result of physical collisions and blunt force trauma (216, 401). The present study found that participation in Rugby League match-play, which is characterised by repeated eccentric muscle contractions of the lower limbs, intermittent high intensity exercise and blunt force trauma resulting from high speed collisions between and among players, significantly increased plasma [CK] and is consistent with the findings of others (259, 426).

The CK values were found to be elevated in players 24 hr pre-match following a period of complete rest (~256 $U.L^{-1}$ ± 123.049). Other research has also reported elevated CK levels pre-competition (179, 424, 426). Suzuki et al., (424) and Takarada (426) reported [CK] of approximately 351.6 $U.L^{-1}$ and 400 $U.L^{-1}$ 48 hr pre-match and same day pre-match respectively in Japanese college rugby players. Gill et al., (179) reported CK activity of 1023.0 $U.L^{-1}$ 3.5 hr pre-match in elite rugby players. The elevated pre-match [CK] found in the present study is likely to indicate residual muscle damage due to game simulated contact training activities or the result of cumulative muscle damage associated with the demands of competitive game participation prior to the commencement of the present investigation.

The CK mean values increased from 30 min pre-match to 30 min post-match (302.83 $U.L^{-1}$ ± 144.07 to 454.83 $U.L^{-1}$ ± 209.36) followed by a significant increase of 91 % in [CK] 24 hr post match (454.83 $U.L^{-1}$ ± 209.36 to 889.25 $U.L^{-1}$ ± 538.27). The increase in [CK] 30 min post-match agrees with results of others (179, 424, 426) and indicates an acute response in CK activity to match-play trauma associated with the degree of impact during collisions. Other research has reported similar (Suzuki et al., (424) 715.4 ± 438.3 $U.L^{-1}$) and greater CK levels following competitive match-play in rugby union, (Takarada (426), 1081 ± 159 $U.L^{-1}$, Gill et al., (179) 2194.0 ± 833.7 $U.L^{-1}$).

Peak [CK] in the present study was found 24 hr post-match (889.25 $U.L^{-1}$ ± 538.27) and is consistent with the findings of others (426). Our findings contrast the results reported by Gill et al., (179) however, who observed peak [CK] immediately following rugby match-play. The findings of the

present study therefore are consistent with the concept that peak [CK] is delayed 24 to 96 hr post competition (216, 259, 355, 426) and support to the practice of prolonging the sample collection period post competition to accurately assess muscle damage and provide direction with respect to the post-match recovery process.

Methodological differences may explain the discrepancy between [CK] observed in the present study and the studies of Takarada (426), Suzuki et al., (424) and Gill et al., (179). The present study reported [CK] at each time point pre-match and post-match as mean values while Takarada (426), Suzuki et al., (424) and Gill et al., (179) only reported peak CK activity. The rationale for reporting mean [CK] in the present study at each time point pre-match and post-match was to identify the overall adaptation of players from all positions during competitive match-play. Peak [CK] in response to competition highlights the response of a single player to match participation and the [CK] response of any single player may therefore be determined by playing position and or skill level leading to error in match-play analysis.

Although no significant positional difference was evident between [CK] and total distances travelled during the match, the backs covered greater distance at high-intensity running (135 ± 49 m; $p = 0.03$) and sprinting speeds (290 ± 69 m; $p < 0.01$) compared to the forwards (82 ± 21 m & 149 ± 32 m respectively). The repeated high intensity acceleration and deceleration associated with sprinting efforts seen in backs, requires considerable eccentric muscle activity in the hamstring muscles. An increased likelihood of structural damage associated with eccentric muscle activity may have contributed to the CK response of the backs. Alternatively, the exposure of forwards to repetitive high intensity collisions may have contributed to acute soft tissue trauma and structural damage to muscle tissue.

Sampling differences may also offer an alternative explanation for variation between the present study and others (179, 426) regarding greater [CK] in response to match-play in contact sports reported previously. The present study examined capillary blood samples whilst Takarada (426) examined venous blood samples and Gill et al., (179) sampled interstitial fluid. On the basis that muscle damage results in CK leakage from the muscle cells into the interstitial fluid before entering the blood through the lymphatic system, it is conceivable that [CK] in the interstitial fluid is greater than in blood due to partitioning effects (179).

The present study examined two hormones that represent the major catabolic and anabolic profile in response to contact sport participation. Testosterone is the dominant anabolic marker for protein signalling and glycogen synthesis (410). Cortisol was also examined in the present study on the basis that it is dependent on the type, intensity and duration of exercise (354) and is influenced by

psychological stress (379) whereas the T:C ratio was used to monitor the balance between anabolism and catabolism in players throughout the game preparation and recovery process.

The pattern of increased cortisol measured pre-competition in contact sport is well documented (137, 379). An increase in [sCort] from 24 hr pre-match to 30 min pre-match in the present study is consistent with the results of others (379). Increased pre-match cortisol is thought to reflect a psychophysiological mechanism influenced in part by cognitive anticipation and anxiety used by athletes as a pre-competitive arousal and coping mechanism used to manage pre-match stress (214).

Elevated post-match [sCort] found in the present study is consistent with other studies (86, 137, 259) after competitive performance. During match-play, [sCort] increased 69 % from 30 min pre-match to 30 min post-match and is consistent with the results of others (86, 137, 353) who have reported increases in sCort during exercise and competition involving high intensity collision between opposing competitors. The mean [sCort] 30min post-match was more than double baseline measures recorded 24 hr pre-match. Several factors associated with Rugby League match play provide an explanation for the sharp increase in sCort found 30 min post-match.

Rugby League is a form of high intensity, intermittent exercise of 80 min duration involving frequent collisions with opponents and is influenced by psychological factors associated with anxiety and perceived stress. Passelergue et al., (354) identified that raised levels of anxiety and stress associated with competition contribute to elevated cortisol concentration in simulated weight lifting competition. Lac & Berthon (264) reported that the higher the intensity and the longer the duration, the greater the cortisol response to such exercise, while Vanhelder et al., (451) highlighted a stronger adrenal response to intermittent anaerobic exercise in comparison to aerobic exercise. The post-match increase in [sCort] found in the present study may be explained by the interplay of psychological, exercise type and the duration of exercise experienced during Rugby League match-play.

After the peak in [sCort] measured 30 min post-match there was a significant reduction in [sCort] 24 hr post game (- 32 %) and 48 hr post match (- 37 %), decreasing [sCort] to below 24 hr pre-match concentrations. The return of [sCort] toward 24 hr pre-match levels within 24-48 hr post-match is consistent with others (137, 259, 353) who have reported a progressive decrease in cortisol post competition. During the post-match recovery phase, sCort sampling took place at 4pm on a daily basis at 24 hr intervals for 5 days post-match. There were further reductions in sCort at 48 hr, 72 hr and 96 hr post-match compared with 24 hr pre-match. Elloumi et al., (137) reported a similar pattern of progressively reduced cortisol levels in rugby players from the first to fourth day post-match. The progressive decline in [sCort] identified during the recovery phase in the present study is in agreement with previous reports describing the sCort response following competition (86, 353) and is reflective

of a return to hormonal homeostasis and removal of the psychological and physical stress associated with match-play.

A non-significant increase in [sCort] was found 120 hr post-match; however, [sCort] remained below 24 hr pre-match levels. The trend for cortisol concentration to become elevated toward the end of the training week in preparation for the next match is consistent with the results of others (137) and in the present study is indicative of a return to high intensity pre-competition sport specific training and the accompanying stress associated with team selection and performance expectations.

In contact sports, changes in testosterone concentration typically do not occur immediately post competition however increases have been identified during a subsequent period of recovery following rugby union match-play and wrestling competition (137, 353). The expected pattern of response of sTest during competitive Rugby League match-play is unclear. In the present study, [sTest] decreased significantly ($p < 0.05$; - 47 %) 30 min pre-match in comparison to 24 hr pre-match baseline levels. Although the match-play resulted in a small increase in sTest (+ 14 %), [sTest] remained significantly reduced compared to 24 hr pre-match, supporting the results of others that have reported a reduction (86, 137) in [sTest] post contact sport participation. The present results disagree with the findings of other researchers (216, 259) who reported no change in testosterone in American Football players following match-play. The inconsistency between our results and the results of others (216, 259) is likely due to considerably greater metabolic requirements of Rugby League match-play in comparison to a game of American Football.

After the match, a return to normalised [sTest] was evident with no significant difference between [sTest] at 24 hr post-match in comparison to 24 hr pre-match. The return to 24 hr pre-match [sTest] within 24 hr of competitive match-play are in contrast to the work of Elloumi et al., (137) who reported higher testosterone levels in rugby union players in the presence of reduced cortisol during a 6 day post competition period in comparison to values measured at rest. Considerable variation in the positional play requirements, match-play intensity and post-match recovery protocols may have contributed to inconsistency between our results and those reported following Rugby Union match-play (137).

The results of the present study clearly identify a pre-competition anticipatory decrease in sT:C influenced by pre-match anxiety and perceived stress in elite Rugby League players. The combination of substantially increased [sCort] and reduced [sTest] identified 30 min pre-match in comparison to 24 hr pre-match baseline measures resulted in a low sT:C and predominant catabolic hormonal environment. The subsequent catabolic environment associated with a low sT:C prior to match-play in the present study is likely to be a reflection of the diversity of [sTest] and [sCort] pre-match. Our

results are in contrast the findings of Elloumi et al., (137) who reported game day [sCort] and [sTest] unchanged in comparison to rest. Subsequently, Elloumi et al., (137) found similar game day T:C in comparison to resting levels in rugby union players. Our results are consistent with Cormack et al., (86) who identified a similar pre game pattern in Australian Rules Football players and reported a substantial decrease in T:C immediately pre-match in comparison to 48 hr pre-match.

A substantial drop in sT:C 30 min post-match in comparison with 24 hr pre-match produced the lowest sT:C found during the pre-match or post-match data collection period in the present study. Despite a 97 % increase in sT:C 24 hr post-match in comparison to the 30 min post-match level, sT:C remained significantly lower than baseline levels, representing a persistent catabolic hormonal profile. The prolonged catabolic hormonal profile of players following Rugby League match-play has implications for post-match recovery and subsequent match preparation on the basis that matches may be scheduled with a few as 4 days separating match-play in the NRL.

A return to baseline measures of both [sTest] and [sCort] at 48 hr post-match is reflected in a reciprocal recovery of sT:C to baseline levels within the same time period. The normalisation of sT:C remained evident in the present study at 72 hr and 96 hr post-match and preceded a drop in sT:C 120 hr post-match in comparison to baseline levels. The reduction in sT:C that occurred 5 days post-match may reflect a return to higher intensity pre-competition sport specific training and the associated increased demand on the endocrine system.

The acute and short term recovery phase findings with respect to sT:C in the present study are consistent with the findings of others (86, 137) who have examined the recovery patterns of contact sport athletes following competitive performance. With respect to the acute 30 min post-match sT:C response, Elloumi et al., (137) reported a substantial reduction in sT:C at the end of an international level Rugby Union match. Conversely however, during the short term recovery phase, our findings contrast those of Elloumi et al., (137) who reported a high sT:C from day 1 to day 5 post match in excess of baseline measures. Our results reflect the findings of Cormack et al., (86) who reported a 36 % decrease in sT:C from pre-match to post-match. The acute decrease in sT:C is likely a function of significantly increased [sCort] and little or no change in [sTest] immediately following match-play. During the short term post-match recovery phase, our results are inconsistent with Cormack et al., (86) who found substantially reduced sT:C in all comparisons from 48 hr pre-game to 120 hr post-game following Australian Rules Football performance suggesting a prolonged catabolic hormonal profile despite 5 days of recovery.

The explanation for variation in short term recovery rates in athletes from collision sports such as Rugby League is multi-factorial. The influence of individual biological responses, specialised team

recovery protocols including nutrition and hydration regimes, travel commitments and weekly team training schedules all contribute to a players' ability to recover from match play in an optimal time frame. The use of sT:C to represent the anabolic:catabolic hormonal profile of athletes following competition has implications for the design and implementation of training programs, particularly in a team sport environment competing in a prolonged regular season period such as 24 matches in a 26 week period as seen in the NRL. The return of the post-match T:C to baseline measures identified in the present study within 48 hr is indicative of a successful recovery of [sTest] and [sCort] and thereby represents a restoration of resting anabolic:catabolic hormone profile in elite rugby league players.

5.5 Practical Applications

The present study provides an insight to player movement patterns during elite Rugby League match play using contemporary GPS performance analysis methods that have not been reported previously. Our findings indicate that the demands of elite Rugby League match-play result in significant skeletal muscle damage and is reflected by peak [CK] measured 24 hr post-match. Elevated [CK] persisted in comparison to pre-match levels despite 120 hr of modified activity post-match suggesting that a prolonged recovery phase of at least 5 days is required to achieve full recovery of muscle damage following match-play.

The endocrine profile depicted in the present study identified a substantial acute sCort and small sTest response to Rugby League match-play followed by a return to homeostasis within 48hrs. A minimum period of 48 hr is therefore recommended to enable hormonal homeostasis to be achieved post-match. The evolution of real time data acquisition with respect to player movement characteristics in team sports will continue to facilitate a more robust and objective analysis and enable sports scientists and coaches to further quantify the requirements of performance. By comparing endocrine and CK responses to performance coaches are able to establish a more tangeable identification of individual responses and adaptation to performance will be achieved in team sports such as Rugby League.

Chapter 6

Markers of Post-Match Fatigue in Professional Rugby League Players.

6.1 Introduction

Participation in contact sport such as Rugby League that involves high intensity, intermittent exercise and blunt force trauma is a complex phenomenon, and is often associated with significant neuromuscular fatigue (for review see Gandevia 2001). Neuromuscular fatigue has been described in humans as any exercise induced reduction in the maximal voluntary force or power produced by a muscle or muscle group (45, 174) and is determined by the type of muscle contraction, the intensity of exercise and the duration of the exercise (140). Traditionally, neuromuscular fatigue has been examined using isolated forms of isometric, concentric or eccentric movements (174). However, recent evidence suggests the incorporation of movements involving the stretch-shortening cycle (SSC) (306) provides a more specific examination of neuromuscular fatigue (250, 325).

Movements involving the SSC incorporate metabolic, mechanical and neural elements of fatigue together with impairment of the stretch-reflex activation (325). Typically, the SSC involves a pre-activated muscle that is first stretched (eccentric action) and then shortened (concentric action) and is common to activities that involve different phases of running, jumping or hopping (250). Recovery following impaired SSC function occurs in two phases; a) identified by a significant initial decrement in SSC function immediately post-exercise and b) a phase of transient recovery then followed by a subsequent decrement in performance, resulting in a peak reduction in SSC function some 48 - 72 hr post exercise (223, 250, 326).

Although the countermovement jump (CMJ) is commonly used to assess the SSC and athletic performance (86, 216, 217, 437), there are limited data that have used the CMJ to determine the effect of competitive team match-play on neuromuscular fatigue. Those data that are available are conflicting (86, 216, 217, 437). Hoffman et al., (216) reported changes in peak power (PP), peak force (PF) and peak rate of force development (PRFD) in American Football players while Thorlund et al., (437) found no significant change in PF, PP or rate of force development (RFD) immediately after a soccer match-play. Similarly, Cormack et al., (86) found no significant change in mean force and mean power immediately after a game of elite Australian Rules Football and suggested that the CMJ may lack the sensitivity to detect neuromuscular fatigue from a single game. There appears to have

been no investigation examining the influence of elite Rugby League match-play on CMJ variables to assess their usefulness as measures of neuromuscular fatigue.

The effects of high intensity, intermittent contact sport match-play on muscle enzyme (e.g. creatine kinase concentration [CK]) and endocrine (eg. salivary cortisol concentration [sCort]) responses have been reported (137, 215, 216, 259, 426). Plasma [CK], an indirect marker of skeletal muscle damage in humans (355), has been reported to be elevated following competitive match-play in American Football (259) and Rugby Union (426). During a competitive Rugby Union match, there was a significant correlation ($r = 0.92$, $p < 0.01$) between the number of tackles performed and peak [CK] measured 24 hr post-match (426). While increases in plasma [CK] have also been reported in other contact sports (259), there are no data reporting the plasma [CK] response to a Rugby League match or during the subsequent 120 hr following a single match.

Cortisol has been used as both an acute and chronic marker of decreased protein synthesis and increased protein degradation during intense exercise (447). Ispirlidis et al., (228) reported plasma cortisol concentration [Cort] to be signifcantly increased immediately after a game of elite Soccer returning to pre-game concentration 24 hr later. Similarily, Cormack et al., (86) found salivary cortisol concentration [sCort] was substantially higher immediately and 24 hr after a game of elite Australian Rules Football. In contrast to these findings, other studies (216, 317) have found no significant changes in [Cort] or [sCort] following inter-collegiate American football and professional soccer match-play respectively. The usefulness of [CK] and [sCort] as markers of post-match neuromuscular fatigue following high intensity and short duration sports is unclear, and particularly so for Rugby League match-play.

Rugby League match-play presents a unique model to study neuromuscular fatigue generated by high intensity competition, combining movement patterns and sprinting profiles similar to Rugby Union, running volumes similar to soccer and blunt force trauma that is characteristic of American Football match-play. Uncertainty remains regarding the pattern of neuromuscular fatigue, plasma CK and cortisol responses to elite contact sport, and the influence of elite Rugby League match-play on neuromuscular fatigue, plasma CK and cortisol is unknown. A better understanding of the neuromuscular, biochemical and endocrine response to competitive match-play and the short-term post-match recovery period is important to planning effective training over the subsequent week and may provide scope for improvement in individualized training and recovery strategies. The aim of the present study therefore was to examine the neuromuscular, biochemical and endocrine responses to Rugby League match-play to determine if the CMJ, plasma CK activity or sCort response could be used to monitor neuromuscular fatigue following a single match. We hypothesize that Rugby League match-play will result in significant skeletal muscle damage, significant elevation of stress hormone

levels and significantly decreased neuromuscular performance during the CMJ post-match. Further, the combination of neuromuscular performance data with plasma CK and sCort provides a more detailed and specific analysis of the demands of Rugby League match-play than achieved previously.

6.2 Methods

6.2.1 Experimental Approach to the Problem

The present study examined SSC performance to determine neuromuscular fatigue following elite Rugby League match-play. Measurement of the dependent variables of PRFD, PP and PF during a CMJ were performed on a portable force plate pre- and post match-play. Plasma [CK] was examined to reflect skeletal muscle damage in response to the demands of match-play. The [sCort] was examined to represent the primary catabolic endocrine measure associated with metabolism pre- and post-match. To examine the acute and short term post-match response of the dependent variables, [CK] and [sCort] were measured via blood and saliva samples respectively. An understanding of player neuromuscular fatigue, skeletal muscle damage and the endocrine response following match-play is important to monitor recovery and effectively manage the pre-match training and preparation process for subsequent matches.

6.2.2 Subjects

Seventeen elite male Rugby League players, age 24.2 ± 7.3yrs, height 188 ± 20.1cm, and mass 94.6 ± 26.8 kg, representing a National Rugby League (NRL) team volunteered to participate in the study. Data were collected during a single match of Rugby League with all participants completing a minimum of 30 minutes (min) of match play in each of the two 40 min halves of the match. Prior to the commencement of the study, participants attended a presentation outlining the purpose, benefits and procedures associated with the study. Written informed consent was obtained from all participants. The study was approved by the Bond University Human Research Ethics Committee (BUHREC) and the Gold Coast Titans Rugby League Football Club.

6.2.3 Procedures

Saliva and blood samples were collected 24 hr pre-match, 30 min pre-match, within 30 min post-match and at 24 hr, 48 hr, 72 hr, 96 hr and 120 hr post-match. The saliva and blood collection

schedule is outlined in Table 21. Subjects were asked to refrain from strenuous exercise 24 hr prior to baseline pre-match saliva and blood sample collection (24 hr pre-match). Saliva and blood samples were collected daily between 1530 hr and 1630 hr with the exception of the 30 min post-match saliva and blood samples that were collected between 1830 hr and 1900 hr due to the time of match-play. Players provided saliva and blood samples within 30 min of match completion and prior to participation in post-match team recovery activities (Table 21). The CMJ was performed on a force plate immediately following each saliva and blood sample collection. Throughout the post-match data collection period (30 min post-match to 120 hr post-match) all subjects participated in all standardised team recovery sessions and weekly team training sessions (Table 21). Active and passive recovery activities are typically implemented following elite Rugby League match-play. Player participation in all post-match recovery sessions was maintained in the present study due to the impracticality of removing this procedure from the regular team routine following match-play. An example of the standardised post-match team recovery and team training week during the in-season period is outlined in Table 22.

6.2.4 The Countermovement Jump (CMJ)

Prior to performing the unloaded CMJ test, subjects completed a warm-up session consisting of 10 min of self paced stationary cycling followed by five min of prescribed dynamic stretching. Once positioned on the force plate, subjects performed one sub-maximal practice jump. Each subject then performed three CMJ, with three minutes rest between each CMJ. The CMJ was commenced in the standing position. The subject then dropped into the squat position and immediately jumped vertically incorporating arm swing to jump as high as possible. The depth of knee flexion and the amount of arm movement used during the CMJ was individually determined by each subject. Take-off from two feet was strictly monitored with no preliminary steps or shuffling permitted during the eccentric or transition phases of the CMJ technique. The best result from the three CMJ's was used for analysis. The CMJ was performed on a commercially available force plate (ONSPOT 2000-1) which sampled at a rate of 1000 Hz and the analogue signal was converted to a digital signal using a PowerLab 30 series data acquisition system (ADInstruments, Sydney, Australia). The vertical force-time data were filtered using a fourth-order Butterworth low-pass filter with a cutoff frequency of 17 Hz.

6.2.5 Calculation of Force Variables

The force-time data from the CMJ included PRFD, PP and PF. A CMJ was deemed to have started when the vertical force exceeded 10 N greater than the mass of the subject. The PRFD was calculated

from the maximum force that occurred over the first derivative of the force-time curve. The PF was calculated as the maximum force achieved over the force-time curve during the CMJ. The vertical velocity was calculated from the integration of the force-time trace and was used to calculate PP. The vertical force was multiplied by the velocity throughout the propulsive phase of the CMJ to determine PP.

6.2.6 Plasma Creatine Kinase Sampling and Analysis

Plasma [CK] was determined from 30 µl capillarized whole blood samples collected via fingertip puncture made using a spring-loaded single use disposable lancet. Blood samples were collected from subjects simultaneously at the time of saliva sample collection. Whole blood samples were centrifuged (Heraeus, Function Line) at 3000 rpm for 10 min, separated plasma was stored at a temperature of - 30 °C until analysis. Plasma samples were analysed using a Reflotron spectrophotometer (Abbott Architect) via an optimised UV-test.

6.2.7 Salivary Cortisol Sampling and Analysis

Unstimulated saliva was collected via passive drool into a plastic tube for analysis of Cortisol. The [sCort] is independent of salivary flow rate (367) and a significant correlation has been reported between saliva and serum unbound cortisol concentration at rest (r = 0.93) and during exercise (r = 0.90) (341). All subjects were requested to avoid the ingestion of food and fluids other than water during the 60 min before providing each saliva sample and refrain from brushing their teeth 2hrs prior to each saliva sample collection session. Subjects were instructed to wait for a period of 10mins following their last consumption of water before commencing the saliva sample collection process. Saliva samples were stored at -80 °C until analysis. [sCort] was analysed in duplicate via a commercially available enzyme-linked immunosorbent assay (Salimetrics, PA, USA) using a microplate reader (SpectraMax 190, Molecular Devices, CA, USA). Standard curves were constructed as per the manufacturer's instructions and commercially available standards and quality control samples were used for the assays (Salimetrics LLC). Cortisol sensitivity was 0.007 ng·mL $^{-1}$ with an average intra-assay CV of 2.6 %. All samples were analysed in the same series in order to avoid inter-assay variability.

Table 21. Counter movement jump (CMJ) testing, specimen collection and training schedule 24 hr pre-match to 120 hr post Rugby League match-play.

Sample	24 hr Pre	30 min Pre	30 min Post	24 hr Post	48 hr Post	72 hr Post	96 hr Post	120 hr Post
Specimen	Saliva Blood	Saliva Blood	Saliva Blood	Saliva Blood	Saliva Blood	Saliva Blood	Saliva Blood	Saliva Blood
Neuromuscular Testing	CMJ	CMJ	CMJ	CMJ	CMJ	CMJ	CMJ	CMJ
Training AM	Nil	Nil	Nil	Recovery 1 CWI / DWR	Nil	Nil	Nil	Nil
Training PM	Team Skills	Pre-Match Warm Up / Match-Play	Post-Match CWI	Recovery 2 Mobility Circuit	Strength Training	Speed Agility Team Skills	Strength Training	Team Skills

Note: DWR = Deep Water Running, CWI = Cold Water Immersion, CMJ = Counter Movement Jump.

6.2.8 Statistical analysis

Endocrine and biochemical variables analysed pre-match and post-match included [sCort] and [CK]. Prior to statistical analysis, log transformation was applied to the endocrine and biochemical data to normalize the distribution and reduce non-uniformity bias. All data are expressed as mean ± SD. Changes in force-power characteristics, biochemical concentrations and endocrine concentrations were analysed using a one-way repeated measures ANOVA. Significant differences were located by a Bonferroni post hoc test. The criterion level for statistical significance was set at $p < 0.05$. The correlation between peak changes in force-power characteristics, biochemical and endocrine characteristics was analysed using the Pearson Product-Moment Correlation Coefficient. The mean coefficient of variation (CV) for CK assays was 6.1 %. All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS for Windows, version 14.0; SPSS, Inc., Chicago, IL).

6.3 Results

Force-Power Characteristics

Changes in the force-power characteristics following elite Rugby League match-play are shown in Table 23. The PRFD was significantly lower 30 min post-match ($p = 0.026$) and 24 hr post-match ($p = 0.042$) compared to 30 min pre-match. PRFD values returned to 24 hr pre-match values 48 hr post-match. However, at 72 hr and 96 hr post-match the PRFD values were significantly higher than both pre-match values ($p = 0.012$ & $p = 0.044$ respectively). PP was significantly lower 30 min post-match ($p = 0.005$) and 24 hr post-match ($p = 0.034$) when compared to 30 min pre-match. PP had returned to 24 hr pre-match and 30 min pre-match levels after 48 hr post-match. PF was significantly lower 30 min post-match ($p = 0.031$) but had returned to 30 min pre-match levels after 24 hr.

Creatine Kinase

There was a significant ($p = 0.003$) increase in plasma [CK] 30 min post-match with a further significant ($p = 0.002$) increase in [CK] , peaking at 24 hr post-match (Table 24). Significant increases in plasma [CK] were also found 48 hr post-match ($p < 0.006$), 72 hr post-match ($p = 0.004$), 96 hr post-match ($p = 0.013$) and 120 hr post-match ($p = 0.043$) compared to 30 min pre-match. There was a significant correlation between plasma [CK] and PRFD 30 min post-match ($p = 0.044$, $r = -0.64$) and 24 hr post-match ($p = 0.033$, $r = -0.58$) compared to 30 min pre-match values.

Cortisol

The [sCort] was significantly ($p = 0.043$) higher 30 min pre-match compared to 24 hr pre-match. Significant increases in [sCort] were also found 30 min post-match ($p < 0.001$) and 24 hr post-match ($p < 0.001$) when compared to 24 hr pre-match (Table 24). The [sCort] was significantly ($p = 0.042$) lower 96 hr post-match compared to 24 hr pre-match. There was a significant correlation between the percent change in [sCort] and PF 30 min post-match ($p = 0.048$, $r = -0.58$) compared to 30 min pre-match values.

Table 22. Force and power characteristics pre- and post Rugby League match-play.

	Peak Rate of Force Development ($N \cdot s^{-1}$)	Peak Power (W)	Peak Force (N)
24 hr pre-match	12653 ± 4195	4340 ± 881	2564 ±738
30 min pre-match	12847 ± 3143	4429 ± 991	2466 ± 479
30 min post-match	8242 ± 2138 *	3123 ± 850 *	2002 ± 313 *
24 hr post-match	9379 ± 2983 *	3479 ± 717 *	2251 ± 354
48 hr post-match	12994 ± 4284	4540 ± 898	2384 ± 493
72 hr post-match	15225 ± 5171 #	4632 ± 959	2550 ± 572
96 hr post-match	15094 ± 3567 #	5050 ± 979	2590 ± 667
120 hr post-match	14066 ± 4832	4485 ± 875	2448 ± 351

Values are mean ± SD. * significantly less ($p < 0.05$) than 30 min pre-match and 48 hr to 120 hr post-match; # significantly greater ($p < 0.05$) than 30 min pre-match (n= 17).

Table 23. An example of a standardised recovery session protocol and typical training week during the in-season phase in elite Rugby League.

Session	Match Day	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
AM	Match day switch on session. Beach / pool swim 20-30 min	Medical check Active exercise CWI Hydration test Physiotherapy 60 min	Team Training (Skills) 60-90 min	Team Training (Wrestle) / Speed Training 60-90 min Post training recovery 30 min	Team Training (Skills) 60-90 min	Active Rest	Team Training (Skills) 60-90 min Post training recovery 30 min
PM	Pre-match warm-up / Match-play 120 min Post-match active exercise* CWI# Hydration Test 60 min	Active Rest	Resistance Training 1 LB Strength & Power / UB Push 60 min 10-15 sets 4-8 RM	Active Rest	Resistance Training 2 UB Strength & Power 60 min 10-15 sets 4-8 RM	Active Rest	Active Rest

* Post-match active exercise – typical exercises include intermittent stationary cycling program (10 min). # Cold water immersion (CWI) – typical protocol ~15min immersion at < 15 °C. Rehydration – Typically includes measurement of pre- and post-match body weight and urine specific gravity (USG) analysis. Refuel – typically includes consumption of light meal comprising 40 g protein and 50 g carbohydrate (CHO) 30 min post-match. Resistance training – typical exercises are as follows: Strength exercises: squat variation, vertical push, vertical pull, horizontal push, horizontal pull. Power exercises: bench throw, squat jump, power clean, push press variations. Team training (Wrestle): Individual / partner attack and defence tackling and ruck play drills. Team Training (Skills): Attack and defensive patterns, game plans and general skills. Post training recovery: Pool deep water running (15 min at 27 °C), general stretching (20 min) and cold water immersion (10 min at < 10 °C), massage (30 min). Speed Training: Typically includes Agility / footwork and reaction drills for 10 min, straight line and change of direction sprints 5-50 m x 4-8 reps, resisted (towing, weighted sled, up hill sprints) / assisted (overspeed bungees, catapault sprints, down hill sprints) 10-40 m x 4-8 reps, plyometric drills (bounding, repeated horizontal jumps, repeated hurdle jumps). RM = repetition maximum. UB = upper body, LB = lower body.

Table 24. Changes in peak plasma creatine kinase (CK) concentration and peak salivary cortisol concentration (sCort) pre- and post Rugby League match-play. (Percent change compared to 24 hr pre-match)

	24 hr Pre	30 min Pre	30 min Post	24 hr Post	48 hr Post	72 hr Post	96 hr Post	120 hr Post
CK ($U \cdot L^{-1}$)	256 ± 113	302 ± 128 (18 %)	454 ± 167 * (77 %)	941 ± 392 * (267 %)	592 ± 201* (131 %)	553 ± 191 * (116 %)	442 ± 154 * (73 %)	365 ± 139 * (43 %)
sCort ($nm \cdot L^{-1}$)	10.1 ± 1.3	13.1 ± 2.6 * (30 %)	21.9 ± 4.4 * (117 %)	15.3 ± 3.5 * (51 %)	9.5 ± 1.4 (-6 %)	9.5 ± 1.6 (-6 %)	7.0 ± 1.1 * (-30 %)	9.2 ± 1.5 (-9 %)

Note: CK = Creatine Kinase; sCort = Salivary Cortisol; * significantly ($p < 0.05$) different from 24 hr pre-match.

6.4 Discussion

The present study examined the neuromuscular, biochemical and endocrine responses to Rugby League match-play to determine if the CMJ, plasma [CK] or [sCort] response could be used to monitor neuromuscular fatigue following competition. The main findings of the present study were a) PRFD and PP measured during a CMJ were decreased for up to 48 hr post-match with PF decreased 30 min post-match. PRFD also increased above pre-match values 72 hr and 96 hr post-match; b) plasma [CK] and [sCort] increased post-match with plasma [CK] remaining elevated for up to 120 hr post-match; c) significant correlations between the change in plasma [CK] and PRFD and the change in [sCort] and PF were found post-match.

Previous work examining force-power variables including PRFD, PF and PP subsequent to team sport participation during Australian Rules Football (86), American Football (216) and Soccer (437) found no significant difference between pre- and post-match force and power measures and suggested that team sport athletes may be able to maintain PRFD, PF and PP following match-play. The results of these studies (86, 216, 437) when compared to the results of the present study are surprising. The competitive requirements of Australian Rules Football, American Football and Soccer that involve periods of sprinting, jumping, rapid changes of direction and blunt trauma could be expected to have an effect on the SSC and a reduction in CMJ performance as found in the present study.

The PRFD, a measure of explosive muscle strength, is an important measure of performance in Rugby League. In the present study, PRFD significantly decreased 30 min post-match and 24 hr post-match in comparison to 24 hr pre-match. The PRFD remained below pre-match values for 48 hr post-match and may reflect the influence of impaired excitation-contraction coupling reported with low-frequency fatigue (LFF) (288) on decreased PRFD, PP and PF 24 hr following Rugby League match-play.

The reduction in PRFD 30 min post-match (35 %) in the present study agrees with some researchers (438) but not others (216, 437). The differences in PRFD, PP and PF between the present study and other studies (216, 437) may be due to the running volumes, sprinting profiles, tackling and wrestling and heavy blunt force trauma demands placed on Rugby League players but not upon Soccer or American Football players during match-play. Although American Football players are likely to experience heavy contact during match-play, episodes of contact involving blunt force trauma are dispersed through protective padding so as to reduce the effect of such trauma upon skeletal muscle tissue. Fewer total blunt force trauma episodes combined with reduced running volumes and extended rest periods between competitive efforts may contribute to the maintenance of PRFD, PP and PF following American Football match-play.

We observed a significant increase in PRFD at 72 hr (18 %) and 96 hr (17 %) post-match that preceded a return to pre-match values 120 hr post-match. Our results regarding PRFD at 72 hr and 96 hr post-match appear to be in contrast to the reported bimodal trend of neuromuscular fatigue involving SSC exercise (250, 325). An immediate decrease in neuromuscular performance following exhaustive SSC exercise has been attributed primarily to metabolic disturbances, (e.g. metabolite accumulation, depletion of energy substrates and phosphate and decrease in mitochondrial respiratory control) (288) while the secondary decrease in neuromuscular performance may coincide with the inflammatory processes associated with muscle damage during exhaustive SSC exercise (146). Studies that reported a bimodal trend of neuromuscular fatigue and recovery (250, 326) used exhaustive eccentric exercise and not team sport activity as used in the present study. Therefore the pattern of PRFD recovery observed at 72 hr and 96 hr post-match may reflect the specific sprinting, SSC activity, blunt force trauma and high intensity intermittent nature of Rugby League match-play and the influence of post-match recovery methods.

The cause of the significant increase in PRFD after 72 hr and 96 hr post-match in the present study is unclear. The CMJ is an effort dependent SSC activity that may have been performed sub-maximally by players' 30 min post and 24 hr post-match. Sub-maximal CMJ effort 30 min post and 24 hr post-match may be one of the consequences of competitive Rugby League match-play, influenced by skeletal muscle soreness and SSC fatigue resulting from high intensity intermittent exercise and repeated blunt force trauma. During competitive Rugby League match-play however, the extent of SSC fatigue may not be exhaustive. Incomplete exhaustion of SSC performance during Rugby League match-play may result in a pattern of post-match PRFD recovery that is not consistent with the bimodal concept of fatigue induced SSC performance decreases and the subsequent short term recovery process.

During the short term post-match recovery period, players completed a structured recovery program of cold water immersion therapy (12 °C), low intensity deep water running and low intensity mobility-resistance exercise (< 40 % 1RM). Strength training that included complex training methods incorporating high intensity loads (> 85 % 1RM) coupled with explosive SSC exercise for the upper and lower limbs was conducted 48 hr post-match. Rugby League specific speed and agility exercise consisting of high intensity, short duration sprint and SSC exercise was conducted 72 hr post-match.

Our results suggest that the explosive strength, speed and SSC exercise conducted during the structured recovery period (48 hr and 72 hr post-match) may have resulted in a compensatory effect observed in PRFD at 72 hr post and 96 hr post-match. The impaired excitation-contraction coupling reported with LFF (423) in the presence of exercise induced muscle damage (250, 288) may have been attenuated by the structured post-match recovery strategies. These structured recovery strategies, if

responsible for the increase in PRFD 72 hr and 96 hr post-match reinforce the need for recovery strategies that enhance the return to pre-match function so that the optimal training stimulus can be provided to players in preparation for subsequent match-play.

Peak power (PP) in the present study was significantly lower 30 min post-match and 24 hr post-match compared to 30 min pre-match values (Table 23). It would appear that both the velocity of the CMJ, evidenced by the reduction in PRFD, and the force as evidenced by the reduction in PF 30 min post-match, may have contributed to the decrease in PP. The decrease in PP remained until 48 hr post-match suggesting that the velocity component of PP was more sensitive to fatigue than the force component. PF decreased significantly 30 min post-match, returning to pre-match values within 24 hr post-match. Not all studies (86, 216, 217) have reported a decrease in PP and PF following competitive match-play or sporting activity. The cause of the decrease in PF observed 30 min post-match as suggested by others (2, 423) may be due to a combination of central fatigue in the form of reduced central drive, and peripheral fatigue in the form of an impairment in action potential propagation over the sarcolemma (high frequency fatigue [HFF]) or impaired excitation-contraction coupling (LFF). The difference between PP and PF found 30 min post-match in the present study and other studies (86, 216, 217) is most likely due to physical demands placed on players from different sports and the incorporation of a structured recovery program during the short term recovery period. Our results indicate that PF (also referred to as maximal strength) recovers more quickly than PP or PRFD following Rugby League match-play.

Other studies (62, 381) have found that PF recovers more rapidly than PP and PRFD. Byrne and Eston (62) reported the recovery of PP after exhausting squat exercise was two days longer than the recovery of isometric strength and suggested that PP, unlike strength which recovers more rapidly, may be affected by delayed onset muscle soreness (451) and the inflammatory responses to exercise-induced muscle damage. While both PF and PP are important qualities in elite Rugby League players (24), PP and PRFD measured during a CMJ may be more useful than PF in monitoring neuromuscular fatigue post Rugby League match-play. The nature of Rugby League match-play includes sprinting, jumping, high speed directional changes and a rapid summation of forces characteristic of PP and PRFD. Significant reductions in PP and PRFD found beyond 24 hr post-match in the present study may reflect the continued influence of LFF and delayed recovery of the neuromuscular system.

In the present study, plasma [CK] and [sCort] were used as indirect markers of muscle damage and physiological stress following Rugby League match-play. Although eccentric muscular work has traditionally been seen as the major contributor to increases in plasma [CK] after exercise (57), recent evidence suggests that significant increases in plasma [CK] may occur as a result of physical impact and blunt force trauma (216, 401, 426). The present study found that participation in Rugby League

match-play, which is characterised by physical impact and blunt force trauma, significantly increased plasma [CK] 30 min post-match, with a peak plasma [CK] occurring 24 hr post-match. Plasma [CK] remained significantly elevated above 24 hr pre-match concentrations for up to 120 hr post-match. The present study adds new knowledge in the time course of [CK] following Rugby League match-play.

Although plasma [CK] as a marker of exercise-induced muscle damage has been challenged (463), plasma [CK] continues to be used as an indirect marker of skeletal muscle damage (57, 259). Our results using plasma [CK] suggests that the exercise-induced muscle damage following Rugby League match-play does occur in significant amounts and remains elevated for at least 120 hr post-match. Peak plasma [CK] (941 ± 392 $U \cdot L^{-1}$) found in the present study are similar to plasma [CK] reported in other sports that involve high impact collisions between players (401, 426). While Takarada (426) recorded similar peak plasma [CK] 24 hr post college Rugby Union match-play, the return to pre-match [CK] was shorter (48 hr) post-match than in the present study. The prolonged elevation of plasma [CK] found from 48 hr post-match until 120 hr post-match in the present study may have also been influenced by recovery strategies during the first 24 hr post-match and the subsequent training sessions undertaken by the players following 48 hr post-match (Table 21).

The effect of elevated [CK] upon athletic performance is unclear. We observed a significant correlation between the increase in plasma [CK] and decreased PRFD 30 min post-match ($p = 0.044$; $r = -0.65$) and 24 hr post-match ($p = 0.033$; $r = -0.58$). Our results suggest that the decrease in PRFD in the present study at 30 min post-match and 24 hr post-match is causally related to the increase in plasma [CK[, consistent with the findings of others (11, 326). Andersson et al.,(11) reported that CMJ height was reduced in the presence of a significant rise in plasma [CK] following elite female soccer match-play. Nicol et al.,(326) also reported an association between an increase in plasma [CK] and decreased drop jump performance during the first two days following exhaustive SSC exercise.

The associated increase in [CK] with decreased PRFD suggests that a CMJ may be used as an indirect estimate of the exercise-induced muscle damage from Rugby League match-play. Support for a CMJ as an indirect estimate of PRFD is based on the reported relationship between [CK] and decreased SSC performance (250). The use of the CMJ as a functional indicator of PRFD, PP, PF and exercise induced muscle damage may therefore provide an appropriate method of functional impairment analysis associated with skeletal muscle damage and recovery times following Rugby League match-play. The association between increased [CK] and decrements in PRFD may be modified by structured recovery programs during the short term post-match recovery period.

In the present study there was a significant increase in [sCort] 30 min pre-match, 30 min post-match and 24 hr post-match compared to 24 hr pre-match. Cortisol is used as an indicator of "physiological stress" imposed during strenuous physical activity (298) and "psychological stress" due to the competitive environment of sport (317). The increase in pre-match [sCort] found in the present study is consistent with the results of others (185) and is likely to be associated with pre-match "psychological stress" due to perceived anticipation and anxiety (353).

In the present study, the peak [sCort] was found 30 min post-match, and by 48 hr post-match [sCort] had returned to 24 hr pre-match concentration. Similar post-match cortisol levels have been reported after games of Australian Rules Football (86), American Football (216) and Rugby Union (137). Elevations in [sCort] have been reported to be dependent on the duration and intensity of exercise (215). The increase in post-match [sCort] found in the present study may be a reflection of exercise duration, intensity and combative nature of Rugby League match-play and psychological influences of anxiety and perceived stress of competition (353).

The present study found a significant correlation between change in [sCort] and the decrease in PF 30 min post-match ($p = 0.048$; $r = -0.58$). No other study has examined the relationship between [sCort] and PRFD, PP and PF following Rugby League match-play. Although it is not clear what the relationship between decreased PF and increased [sCort] may be, our results indicate that those players with the largest decrement in PF also produced the highest [sCort] 30 min post-match. Decreased PF may reflect neuromuscular fatigue via a Rugby League match-play induced decline in central drive and failure of the excitation contraction mechanism (2) in players who experienced greater psychological stress or completed more high intensity activity for longer duration, resulting in higher post-match [sCort].

In summary, the findings of the present study indicate that the PRFD measured during a CMJ may be used as a mechanism to determine the neuromuscular fatigue associated with competitive Rugby League match-play. Elevated plasma [CK] for up to 120 hr post-match suggests significant damage to muscle tissue as a result of the blunt force trauma associated with high speed collisions among Rugby League players. These neuromuscular and biochemical markers show promise as predictors of neuromuscular fatigue, recovery and readiness for subsequent training following a Rugby League match-play.

6.5 Practical Applications

The ability to quantify decrements in key performance indicators such as lower body force and power characteristics, and establish the neuromuscular status of players post-match via an easy to administer functional test enables coaches to make informed decisions regarding recovery protocols and subsequent training programs and schedules. Our findings indicate skeletal muscle damage occurs as a result of the rigors of elite Rugby League match-play, and is reflected by peak [CK] measured 24 hr post-match. Elevated [CK] persisted in comparison to pre-match levels despite 120 hr of modified activity post-match suggesting a prolonged recovery phase of at least 5 days is required to achieve a full recovery of muscle damage following match-play. The [sCort] profile depicted in the present study identified a substantial acute [sCort] increase in response to Rugby League match-play followed by a return to homeostasis within 48 hr. A minimum period of 48 hr of modified activity post-match is therefore recommended to enable [sCort] to return to pre-match rested levels.

Peak rate of force development, PP and PF returned to pre-match levels within 48 hr post-match, indicating an absence of neuromuscular fatigue and a preparedness of players to undertake strength training despite a prolonged presence of muscle damage as indicated by elevated [CK]. The present study found that a return to modified strength training activities 48 hr post-match may result in a compensatory increase in PRFD and supports the early implementation of strength training methods to facilitate the short term post-match recovery period. By comparing neuromuscular, biochemical and endocrine responses to match-play, coaches are able to establish a comprehensive profile of individual responses and adaptation to elite Rugby League match-play.

Chapter 7

Biochemical and Endocrine Responses to Impact and Collision During Elite Rugby League Match-Play.

7.1 Introduction

Exercise induced muscle damage has been examined in humans (216, 263) with plasma creatine kinase (CK) activity commonly reported as an indirect marker of skeletal muscle damage in sports (215, 355, 426). The extent of skeletal muscle damage has been related to the intensity and duration of exercise (439). High intensity eccentric exercise has traditionally been considered the primary factor associated with skeletal muscle damage (363). Typically, skeletal muscle damage is associated with morphological changes within the muscle cell that are accompanied by the leakage of proteins such as CK out of the cell and into the blood circulation via the lymphatic system (224).

Elite Rugby League match-play is synonymous with intermittent high intensity exercise, repeated blunt force trauma, skeletal muscle damage and post exercise muscle soreness. Elevated plasma CK concentration ([CK]) has been reported following competitive match-play in contact sports (179, 215, 259, 401, 424, 426) suggesting that significant skeletal muscle damage occurs during such contact sports. Takarada (426) reported a significant correlation between the number of tackles performed during Rugby Union match play with peak [CK] measured 24 hr post-match. Suzuki et al., (424) also found significant increases in [CK] immediately following Rugby Union match-play that remained elevated 24 hr post-match. Although increases in plasma [CK] have been reported in contact sports (179, 259, 401, 426) the CK response to impact associated with collisions during elite Rugby League match-play is unkown.

Although the effects of contact sport competition on the acute endocrine responses (86, 137, 216, 259) and the post-competition recovery period (137, 259) have been reported, this is not the case for elite Rugby League. Cortisol has a role as a stress hormone and its presence has been identified as a marker of the endocrine response to competitive high intensity combative sports (137, 149). The salivary cortisol concentration ([sCort]) provides a valid and reliable estimation of serum unbound cortisol (65, 456). The effect of repeated high velocity collisions and high running volumes that are characteristic of Rugby League match-play provides a unique model in which to examine the time course of endocrine responses to competition. Previous work (86, 137) with other collision based

sports have reported increased [sCort] immediately following, and 24 hr after competition. There appears to have been no investigation examining the time course of the [sCort] response to repeated blunt force trauma and high velocity collisions during elite Rugby League match-play beyond 24 hr post-match.

Recent studies (246, 396) have added to our understanding of player movement characteristics during Rugby League match-play. Advances in match analysis methodologies incorporating Global positioning systems (GPS) and integrated accelerometer technologies, have enabled investigators (111) to accurately quantify activity profiles and the impact associated with collisions during contact sport match-play. Further, accurate determination of gravitational forces (G) experienced by players during repeated collisions with opponents during match-play provides new insight into the physical consequences of contact sport competition.

The movement patterns of elite Rugby League players during competitive match-play using GPS and integrated accelerometer technology have been reported (304, 305), however there are no data that describe the G forces experienced by players during high velocity collisions that are synonymous with elite Rugby League match-play. Skeletal muscle damage due to high intensity eccentric exercise such as that found in Rugby League match-play has been associated with decreased muscle function and performance (84). Uncertainty remains regarding the pattern of plasma CK and endocrine responses to elite level contact sport, and the influence of blunt force trauma and impact during Rugby League match-play is unknown. A greater understanding of the biochemical and endocrine responses of elite players to Rugby League match-play may provide scope for improved and individualised post-match recovery strategies, reduce the risk of residual and or cumulative neuromuscular fatigue and potentially decrease the incidence of musculoskeletal injury.

The aim of the present study was to examine the acute and short term biochemical and endocrine responses to the intensity, number and distribution of impacts associated with collisions among players and contact with the playing surface during Rugby League match-play. We hypothesize that blunt force tauma associated with impacts that are characteristic of Rugby League match-play will result in significant skeletal muscle damage and significantly increased stress hormone concentrations post-match. Further, the combination of impact related GPS and accelerometer match-play data with plasma CK, sCort and sTest provides a more detailed and specific analysis of the demands of Rugby League match-play than achieved previously.

7.2 Methods

7.2.1 Experimental Approach to the Problem

A single group repeated measures pre-post match design was used in the present study. To examine the impact characteristics of the independent variable of player collisions during elite Rugby League match-play, GPS data and accelerometer data were collected from players during a match of 80 minutes (min) duration between two National Rugby League (NRL) teams. Plasma [CK] was examined to reflect skeletal muscle damage in response to collisions experienced by players during match-play. Salivary cortisol (sCort) was examined to represent the primary catabolic endocrine measure associated with metabolism pre- and post-match. To examine the pre-, during, and post-match response of the dependent variables, [CK] and [sCort] were measured via blood and saliva samples respectively. All participants played a minimum of 30 min in each of the two 40 min halves of the match. Players were separated into forwards and backs positions for comparison. An understanding of the effects of repeated blunt force trauma and the characteristics of impacts associated with collisions during match-play on the endocrine responses and skeletal muscle damage markers following elite Rugby League match-play is important to determine post-match recovery strategies, monitor residual and or cumulative neuromuscular fatigue throughout the competitive season and effectively manage player preparation for subsequent matches.

7.2.2 Subjects

Seventeen elite male Rugby League players, age 24.2 ± 7.3yrs, height 188 ± 20.1cm, and mass 94.6 ± 26.8 kg; (mean ± SD), representing an NRL team volunteered to participate in the study. Due to the minimum time on field match-play requirements, data were analysed from fifteen players (Forwards n = 8; Backs n = 7). Prior to the commencement of the study, players attended a presentation outlining the purpose, risks, benefits and procedures associated with the study. All players were made aware of their ability to withdraw from the study at any time and for any reason. Written informed consent was obtained from all players who participated in the study. The study was approved by the Bond University Human Research Ethics Committee (BUHREC) and the NRL club from which players volunteered.

7.2.3 Procedures

Saliva and blood samples were collected 24 hr pre-match, 30 min pre-match, within 30 min post-match and at 24 hr, 48 hr, 72 hr, 96 hr and 120 hr post-match. The daily training and saliva and blood collection schedule is outlined in Table 25. Subjects were asked to refrain from strenuous exercise during the 24 hr prior to baseline saliva and blood sample collection (24 hr pre-match). Saliva and blood samples were collected daily between 1530 hr and 1630 hr with the exception of the 30 min post-match saliva and blood samples that were collected between 1830 hr and 1900 hr due to the scheduled time of match-play. Players provided saliva and blood samples within 30 min of match completion and prior to participation in post-match recovery activities. Data were examined for each subject at each saliva and blood sample collection time point. Throughout the post-match data collection period subjects participated in all of the teams scheduled post-match recovery and daily training sessions (Table 25).

7.2.4 Plasma Creatine Kinase Sampling and Analysis

Plasma [CK] was determined from 30 µl capillarized whole blood samples collected via fingertip puncture made using a spring-loaded single use disposable lancet. Blood samples were collected from subjects simultaneously at the time of saliva sample collection (Table 25). Whole blood samples were centrifuged (Heraeus, Function Line) at 3000 rpm for 10 min, separated plasma was stored at a temperature of -30 °C until analysis. Plasma samples were analysed in duplicate using a Reflotron spectrophotometer (Abbott Architect) via an optimised UV-test.

7.2.5 Salivary Cortisol Sampling and Analysis

Unstimulated saliva was collected via passive drool into a plastic tube for analysis of [sCort]. Saliva measures of [sCort] are independent of flow rate (367) and there is a significant relationship between saliva and serum unbound cortisol at rest ($r = 0.93$) and during exercise ($r = 0.90$) (341). All subjects were requested to avoid the ingestion of food and fluids other than water in the 60 min before providing each saliva sample and to refrain from brushing their teeth 2 hr prior to each saliva sample collection session. Subjects were instructed to wait for a period of 10 min following their last consumption of water before commencing the saliva sample collection process. Saliva samples were stored at a temperature of -80 °C until analysis. Saliva Cortisol [sCort] was analysed in duplicate via a commercially available enzyme-linked immunosorbent assay (Salimetrics, PA, USA) using a

microplate reader (SpectraMax 190, Molecular Devices, CA, USA). A standard curve was constructed per the manufacturer's instructions and commercially available standard and quality control samples were used for both assays (Salimetrics LLC). Assay sensitivity was 0.007 $ng \cdot mL^{-1}$ for sCort with intra-assay coefficient of variation (CV) as a percentage of 2.6 %. All samples were analysed in the same series in order to avoid possible inter-assay variability.

7.2.6 Match Analysis

The present study used commercially available 5 Hz GPS receivers (SPI-Pro, GPSports, Canberra, Australia) which operated in non-differential mode and provided data in real time. The GPS is a satellite-based navigation system that enables real-time data collection during training and competition (89, 111, 289). Information with respect to the intensity, number and distribution of gravitational forces (G) experienced by players during collision are recorded simultaneously via satellite communication with a portable GPS receiver and integrated accelerometer worn by a player. The GPS typically utilises a network of 24 satellites in orbit around earth. Each satellite is equipped with an atomic clock that emits, at the speed of light, the exact time and position of the satellite. The GPS receiver compares the time emitted by each satellite signal with the lag time, measured by each receiver, translated into distance by trigonometry. By calculating the distance to at least four satellites, the exact position and altitude of the receiver on the Earth's surface can be determined (443). Speed of displacement is determined via the Doppler shift method, by measuring the rate of change of the satellites' signal frequency attributable to movement of the receiver (443).

The SPI-Pro GPS units used in the present study contain a tri-axis (x, y, z axis) integrated accelerometer which measures accelerations in gravitational force (G-force) on three planes, namely forwards and backwards, up and down and tilt left and right. The integrated accelerometer within the GPS unit measures accelerations and decelerations (ms^2) for each plane, with known gravity of 9.8 ms^2 equal to 1 G. The integrated accelerometer measures the rate of acceleration and deceleration on each plane and divides the value by 9.8 ms^2 to determine the combined G-force as the sum of the G-force measured on each directional axis. The GPS model used in the current study (76 g; 48 mm x 20 mm x 87 mm) was worn in a purpose designed vest (GPSports, Australia) to ensure that range of movement of the upper limbs was not restricted. The GPS unit was worn in a padded mini backpack contained in the vest and positioned in the centre area of the upper back slightly superior to the shoulder blades at the level of approximately thoracic vertebrae one (T1).

Participants had previously worn the GPS units during outdoor training sessions that included Rugby League specific running, skill related and match simulated contact activities during a sixteen week pre-season training period. Participants had also worn the units in two pre-season practice matches conducted seven days and fourteen days prior to the match examined in the present study. No participants complained of discomfort or impediment to their normal range of movement or performance from wearing the GPS equipment during training or competitive match-play. Data provided from the GPS unit for examination in the present study included impact (G Force) data (intensity, number and distribution) total distance, speed and heart rate (HR) characteristics. Raw accelerometer data were available in real time via Wireless Fidelity (WiFi) communication and were displayed using commercially available software (Team AMS, GPSports, Australia). The reliability of the SPI-Pro has been reported previously (356) and has been assessed by our laboratory over distances from 5 m to 8000 m on a synthetic 400 m athletics track with < 3% variation in total distance and the reliability of speed assessed with electronic light gates (Smart-speed, Fusion Sport, Australia) from walking speed (6.0 km/hr^{-1}) to maximum sprint speed (> 22.0 km/hr^{-1}) with variation < 5.5 %. Our results are similar to the results of others (356).

7.2.7 Impact Classification System

Player exposure to impact was determined via accelerometer data provided in gravitational (G) force. A zone classification system forms the basis of the analysis performed by the Team AMS software, allowing six ranges impact (Zone 1-6) to be pre-set and used for subsequent analysis. Zone one indicates the lowest impact or lowest intensity of collision with each zone progressively categorising impact force and movement intensity to zone six indicting the highest impact and intensity of movement. The impact classification system used in the present study was based on methods used in Rugby Union (111) and manufacturer guidelines (GPSports, Australia). Each impact was coded to one of six zones based on acceleration G force characteristics recorded by the GPS unit and the integrated accelerometer. Impact zone characteristics used in the present study are listed in Table 26.

Table 25. Saliva and blood sample collection and training schedule 24 hr pre-match to 120 hr post-match.

Sample	1	2	3	4	5	6	7	8
Time	24 hr Pre	30 min Pre	30 min Post	24 hr Post	48 hr Post	72 hr Post	96 hr Post	120 hr Post
Specimen	Saliva & Blood	Saliva & Blood	Saliva & Blood	Saliva & Blood	Saliva & Blood	Saliva & Blood	Saliva & Blood	Saliva & Blood
AM	Off	Off	Off	Recovery 1	Off	Off	Off	Off
PM	Team Skills	Match	Match	Recovery 2	Strength Training	Team Skills	Strength Training	Team Skills

Table 26. Impact zone classification using Team AMS software.

Zone	Gravitational force (G force)	Collision classification
1	< 5.0 - 6.0	Very light impact, hard acceleration, deceleration or change of direction while running.
2	6.1 - 6.5	Light to moderate impact, minor collision with opposition player, contact with the ground.
3	6.5 - 7.0	Moderate to heavy impact, performing a tackle or being tackled at moderate velocity.
4	7.1 - 8.0	Heavy impact, high intensity collision with opposition players, performing a direct front on tackle on opponent travelling at moderate velocity, being tackled by multiple opposition players when running at sub-maximum velocity.
5	8.1 - 10.0	Very heavy impact, high intensity collision with opposition players, performing a direct front on tackle on opponent travelling at high velocity, being tackled by multiple opposition players when running at near maximum velocity.
6	> 10.1	Severe impact, high intensity collision with opposition players, performing a direct front on tackle on opponent travelling at high velocity, being tackled by multiple opposition players when running at maximum velocity.

7.2.8 Tackle Count and Hit Up Number Data

The average number of tackles and the number of ball carries (hit ups) completed by playing position for forwards and backs was determined by post-match analysis of video recordings of match-play (Table 27). For the purposes of the present study, a tackle was defined as an event that halted the progress of an opponent in possession of the ball. A ball carry (hit-up) for the purposes of the present study was defined as a player being tackled in possession of the ball during match-play.

Table 27. Average number of tackles, hit-ups and biochemical concentrations for forwards, backs and all players combined following Rugby League match-play.

	Forwards (n = 8)	Backs (n = 9)	All players (n = 17)
Tackles	20.1 ± 11.3 *	10.7 ± 8.0	14.9 ± 10.5
Hit-ups	10.9 ± 4.2	9.7 ± 3.5	10.2 ± 3.8
Peak Plasma [CK] ($U \cdot L^{-1}$)	979 ± 415	922 ± 380	941 ± 392
Peak [sCort] ($nmol \cdot L^{-1}$)	23.2 ± 4.7	19.6 ± 4.1	21.9 ± 4.4

Note: [CK] = Creatine Kinase concentration, [sCort] = salivary cortisol concentration; * significant difference ($p < 0.05$) compared with backs. Data are expressed as mean ± SD.

7.2.9 Statistical Analysis

Biochemical and endocrine variables analysed pre-match and post-match included plasma CK and [sCort]. Prior to statistical analysis, log transformation was applied to the biochemical and endocrine data to normalize the distribution and reduce non-uniformity bias. The data for each of the dependent variables are represented as mean (± *SEM*) using standard statistical methodology. Changes in biochemical and endocrine concentrations were analysed using one-way repeated measures ANOVA. Significant differences were identified via a Bonferroni post hoc test. Differences in tackles, hit-ups, impact zones and peak biochemical data between backs and forwards were determined using Student's unpaired *t*-test. The criterion level for statistical significance was set at $p \leq 0.05$. The correlation between peak changes in biochemical and endocrine markers, total tackles, number of hit-ups and impact zones were analysed using the Pearson product-moment correlation coefficient. The data are expressed as mean ± SD. All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS for Windows, version 14.0; SPSS, Inc., Chicago, IL).

7.3 Results

Creatine Kinase

Plasma [CK] measured from 24 hr pre-match to 120 hr post-match are found in Table 28. In comparison to 30 min pre-match, a significant ($p = 0.003$) increase in plasma [CK] was found 30 min post-match with a further significant ($p = 0.002$) increase and peak plasma [CK] 24 hr post-match (Table 28). The peak plasma [CK] for forwards and backs was 979 ± 415 $U \cdot L^{-1}$ and 922 ± 380 $U \cdot L^{-1}$ respectively. Significant increases in plasma [CK] were also found 48 hr post- ($p < 0.006$), 72 hr post- ($p = 0.004$), 96 hr post- ($p = 0.013$) and 120 hr post-match ($p = 0.043$) compared to 30 min pre-match. Impact zones 5 and 6 were significantly correlated to plasma [CK] 30 min post-match and at 24 hr, 48 hr and 72 hr post-match (Table 29). The number of Zone 4 entries was significantly correlated to plasma [CK] 30 min post-match and 24 hr post-match (Table 29). The number of hit-ups performed during match-play was significantly correlated ($p < 0.05$) to plasma [CK] at 24 hr, 48 hr and 72 hr post-match (Table 29).

Cortisol

The [sCort] from 24 hr pre-match to 120 hr post-match are listed in Table 28. The [sCort] was significantly ($p = 0.043$) higher 30 min pre-match compared to 24 hr pre-match. Significant increases in [sCort] were also found 30 min post-match ($p < 0.001$) and 24 hr post-match ($p < 0.001$) compared to 24 hr pre-match (Table 28). There was no significant difference between [sCort] at 48 hr post-match in comparison to 24 hr pre-match. Despite significant increases in [sCort] immediately post-match and 24 hr post-match there was no significant correlation between [sCort] and the number of tackles performed, the number of hit-ups or the number of impact related entries in Zone 4, 5 or 6 by forwards or backs during match-play, or throughout the course of the 120 hr post-match recovery period.

Table 28. Changes in peak plasma [CK] and peak [sCort] pre and post Rugby League match-play. (Percent change compared to 24 hr pre-match)

	24 hr Pre	30 min Pre	30 min Post	24 hr Post	48 hr Post	72hr Post	96 hr Post	120 hr Post
Plasma [CK] ($U \cdot L^{-1}$)	256 ± 113	302 ± 128 (18 %)	454 ± 167 * (77 %)	941 ± 392 * (267 %)	592 ± 201* (131 %)	553 ± 191 * (116 %)	442 ± 154 * (73 %)	365 ± 139 * (43 %)
[sCort] ($nmol \cdot L^{-1}$)	10.1 ± 1.3	13.1 ± 2.6 * (30 %)	21.9 ± 4.4 * (117 %)	15.3 ± 3.5 * (51 %)	9.5 ± 1.4 (- 6 %)	9.5 ± 1.6 (- 6 %)	7.0 ± 1.1 * (- 30 %)	9.2 ± 1.5 (- 9 %)

Note: [CK] = plasma creatine kinase concentration, [sCort] = salivary cortisol concentration; * significantly ($p < 0.05$) different from 24 hr pre-match. (n = 17). Data are expressed as mean ± SD.

Table 29. Significant correlations between hit-up number, impact zone entries and plasma [CK] immediately following Rugby League match-play ($p < 0.05$).

		Hit-up number	Impacts zones		
			4	5	6
Plasma [CK] ($U \cdot L^{-1}$)	30 min post	-	0.627 ($p = 0.041$)	0.625 ($p = 0.040$)	0.609 ($p = 0.041$)
	24 hr post	0.617 ($p = 0.043$)	0.634 ($p = 0.036$)	0.744 ($p = 0.009$)	0.765 ($p = 0.005$)
	48 hr post	0.629 ($p = 0.038$)	-	0.585 ($p = 0.042$)	0.592 ($p = 0.038$)
	72 hr post	0.621 ($p = 0.041$)	-	0.554 ($p = 0.045$)	0.545 ($p = 0.046$)

Note: [CK] = plasma creatine kinase concentration. Data are expressed as mean ± SD; (n =17).

Match Analysis

The number of tackles and ball carries for forwards and backs during the match are listed in Table 27. Although there was no significant differences in the number of hit-ups between forwards and backs, forwards completed significantly ($p = 0.043$) more tackles during the match compared to backs (Table 27). There was no significant difference between forwards and backs in peak plasma [CK] and [sCort] following match play (Table 27). Impact zone entries during match-play are listed in Table 30. There was no significant difference in the number of recorded impacts in each zone between forwards and backs. The grouping of match impacts within Zone 4 - 6 (heavy + very heavy + severe) revealed that players experience high-intensity impacts approximately every 50 s during match-play.

Table 30. Average number of impact zone entries for forwards, backs and all players combined during Rugby League match-play.

		Forwards (n = 8)	Backs (n = 9)	All players (n = 17)
Impact zones	1	215 ± 80	214 ± 126	215 ± 110
	2	146 ± 68	154 ± 105	150 ± 90
	3	392 ± 151	334 ± 195	366 ± 172
	4	47 ± 24	50 ± 31	49 ± 28
	5	29 ± 14	26 ± 14	28 ± 14
	6	21 ± 8	20 ± 5	21 ± 8
	Total impacts	858 ± 125	795 ± 145	830 ± 135
	Impact/min (Zone 1-6)	11 ± 2	10 ± 2	10 ± 2
	Impact/min (Zone 4-6)	1.2 ± 0.6	1.2 ± 0.5	1.2 ± 0.6

Note: * significant difference ($p < 0.05$) compared with backs. Data are expressed as mean ± SD.

7.3 Discussion

The findings of the present study indicate that competitive elite Rugby League match-play induces significant damage to skeletal muscle that remains elevated in comparison to pre-match measures for at least 120 hr post-match. The extent of skeletal muscle damage is related to the player impact associated with repeated high intensity collisions during match-play. Increases in the concentration of muscle enzymes such as CK in the blood are indicative of increased skeletal muscle membrane permeability and suggestive of skeletal muscle damage (80). Although eccentric muscular work has traditionally been considered the predominant contributor to increased plasma [CK] after exercise (57), recent evidence suggests that significant increases in plasma [CK] may occur due to physical collisions and blunt force trauma (216, 401, 426). Rugby League match-play is characterised by repeated eccentric muscle contractions, intermittent high intensity exercise and frequent blunt force trauma. The present study found that participation in Rugby League match-play induces structural damage to skeletal muscle tissue and is consistent with others that have used plasma CK to assess the

degree of skeletal muscle damage in contact sports (179, 215, 259, 424, 426). Cunniffe et al., (110) reported elevated plasma [CK] in elite Rugby Union players in a rested state (497 $U.L^{-1}$) and pre-international level match-play (333 $U.L^{-1}$) while Suzuki et al., (424) and Takarada (426) reported [CK] of approximately 351.6 $U.L^{-1}$ and 400 $U.L^{-1}$ 48 hr pre-match and same day pre-match respectively in Japanese college-aged Rugby Union players. Gill et al., (179) reported CK activity of 1023.0 $U.L^{-1}$ 3.5 hr pre-match in elite Rugby Union players. The elevated pre-match plasma [CK] found in the present study is likely to indicate residual skeletal muscle damage arising from Rugby League orientated contact training activities and cumulative skeletal muscle damage resulting from the demands of match-play in the weeks prior to the commencement of the present investigation.

The increase in plasma [CK] 30 min post-match is consistent with the results of others (110, 179, 401, 424, 426) and indicates an acute [CK] response to trauma associated with high speed collisions between and among players during elite Rugby League match-play. The peak plasma [CK] found 24 hr post-match in the present study agrees with results of previous studies in Rugby Union (110, 424, 426) and American Football (259). The present study is the first to examine plasma [CK] following elite Rugby League match-play and adds further support to delayed increase in plasma [CK] for approximately 18-96 hr post competition (80, 259). Our results are in contrast to those of Gill et al., (179) who recorded the highest [CK] immediately following Rugby Union match-play. The difference between the results of the present study and those of Gill et al., (179), may reflect the differences in experimental design between the two studies. The present study examined plasma [CK] 30 min following elite Rugby League match-play and subsequently at 24 hr intervals for a period of 120 hr post-match. The immediate post-match [CK] reported by Gill et al., (179) may not represent peak [CK] due to subsequent sample collection not taking place until 36 hr post-match and 84 hr post-match.

The findings of the present study are consistent with others (424, 426) that have reported peak [CK] may not take place until 24-48 hr post-match. Sampling differences may also offer an alternative explanation for the greater [CK] reported following Rugby Union match-play (179, 426). The present study examined capillary blood samples while Gill et al., (179), sampled interstitial fluid. Muscle damage resulting in CK leakage from the muscle cells into the interstitial fluid before entering the blood stream through the lymphatic system (224) may result in the interstitial fluid [CK] to be greater than in blood due to partitioning effects (179). Plasma [CK] may be further reduced due to metabolism of CK in the interstitial fluid before entering the circulation, resulting in decreased [CK] by comparison.

An increase in [sCort] from 24 hr pre-match to 30 min pre-match is consistent with others (137, 379) that have examined cortisol levels pre-contact sport competition. The pattern of increased pre-match

cortisol is thought to reflect a psychophysiological mechanism influenced in part by cognitive anticipation and self perceived anxiety that is used by athletes as a pre-competition coping and arousal mechanism to manage pre-match stress (214). Elevated [sCort] found in the present study 30 min post-match is consistent with the results of others (86, 137, 259) that have identified a significant ($p < 0.001$) increase in cortisol following competitive performance. The [sCort] increased significantly from 30 min pre-match to 30 min post-match and supports the findings of others (86, 137, 259) who have reported increased cortisol levels in response to exercise and competition involving repeated collisions between opposing competitors. Several performance related factors associated with elite Rugby League match-play provide an explanation for significantly increased [sCort] 30 min post-match in the present study.

Rugby League is a collision sport characterised by high intensity intermittent exercise and repeated blunt force trauma during match-play of 80 min duration, and influenced psychologically by perceived stress and anxiety. Lac & Berthon (264) have reported that the greater the intensity and duration of exercise, the greater the cortisol response, while Passelergue et al., (354) have identified increased cortisol in response to raised anxiety and stress during simulated weight-lifting competition. The significant post-match increase in [sCort] found in the present study is likely to have been influenced by an interplay of psychological factors, such as performance anxiety, match-outcome and perception of performance, the type of exercise and the duration of competition experienced by players during elite Rugby League match-play. Following the peak in [sCort] 30 min post-match a significant reduction in [sCort] was found 24 hr post-match, followed by a further decrease in [sCort] 48 hr post-match to a level below 24 hr pre-match [sCort]. The return to 24 hr pre-match [sCort] within 24-48 hr post-match is consistent with others (137, 259) who have reported a similar pattern of progressively reduced cortisol levels post-competition and reflects the removal of match-related psychological and physical stressors during the short term recovery period.

Despite significant elevations in [sCort] 30 min post-match and during the 24-48 hr post-match period, no relationship was found between [sCort] and the number of collisions experienced by players in the present study. Furthermore, [sCort] was not related to the number of entries in impact Zone 1 to 6 during match-play. No studies have investigated [sCort] in response to elite Rugby League match-play using integrated accelerometer technology to quantify the G force of impacts associated with repeated match-specific collisions. The results of the present study indicate that elite Rugby League match-play is a high intensity form of exercise, generating sufficient physiological and psychological stress (149) to cause a significant increase in [sCort] followed by a return to sCort homeostasis within 48 hr post-match. A non-significant increase in [sCort] was found 120 hr post-match in the present study, however [sCort] remained below 24 hr pre-match [sCort] and was indicative of a daily fluctuation in [sCort] in response to the demands of daily training activities in preparation for

subsequent match-play. The trend for cortisol to increase in preparation of subsequent match-play is consistent with the findings of others (137) and in the present study is indicative of a return to high intensity Rugby League specific training and the accompanying stress associated with individual and team performance expectations.

Body impacts experienced by players during repeated high intensity collisions between opposing players and the playing surface are associated with impact forces in zones 4, 5 and 6. The present study found no significant difference between the total number of impacts and the number of entries in each impact zone between forwards and backs during offensive and defensive match-play. The total number of impacts for forwards and backs during match-play (858 ± 125; 795 ± 145 respectively) was consistent with the total number of impacts recorded for backs (798) but substantially less than forwards (1274) during a case study analysis of the physiological demands of elite Rugby Union match-play (n = 2) using integrated accelerometer data (111). It is likely that considerable time spent performing match-play specific activities such as rucks, mauls, scrums and repetitive contact between opposing players at the breakdown generally in Rugby Union resulted in a high number of total impacts in Rugby Union forwards in comparison to Rugby League forwards. Rugby League match-play however resulted in considerably more very high intensity zone 6 entries (> 10 G forwards 21 ± 8; backs 20 ± 5) in comparison to forwards and backs during a game of elite Rugby Union (> 10 G: forwards 13; backs 4) (111).

The present study found a significant correlation between the number of Zone 4, 5 and 6 entries and plasma [CK] 30 min post-match and 24 hr post-match (Table 30). Furthermore, a significant correlation was also found between the number of Zone 5 and 6 impact entries and plasma [CK] 48 hr and 72 hr post-match. Our results indicate that regardless of the nature of contact, exposure to high impact collisions > 7 G caused significant skeletal muscle damage during match-play that peaked 24 hr post-match. Collisions that involved heavy impacts > 8 G resulted in a prolonged increase in plasma [CK] that remained significantly elevated for at least 72 hr post-match (Table 30). The results of the present study have not been investigated previously and are likely to reflect greater skeletal muscle damage associated with repeated heavy blunt force trauma during high intensity elite Rugby League match-play specific collisions.

The present study found a significant correlation between the total number of hit-ups, total tackles and plasma [CK] 30 min post-match and 24 hr, 48 hr and 72 hr post-match. To differentiate the physical consequences of offensive versus defensive match-play, the present study investigated the relationship between the number of tackles, the number of hit-ups and plasma [CK] independently within 30 min post-match and at 24 hr intervals for a period of 120 hr post-match. The present study found no significant correlation between the number of tackles a player performed and plasma [CK]

immediately post-match, or during the 120 hr post-match recovery period. A significant correlation was found in the present study however between the number of hit-ups performed by players and plasma [CK] 24 hr ($p = 0.043$), 48 hr ($p = 0.038$) and 72 hr ($p = 0.041$) post-match (Table 29).

Our results are consistent with the findings others that have examined [CK] and match-related impacts during Rugby Union match-play (110, 401, 426). Takarada (426) reported a significant correlation between the number of tackles and peak plasma [CK] 24 hr following Rugby Union match-play in Japanese college-aged players. We note that Takarada (426) referred to a tackle as the "total number of times a player tackled or was tackled from in front" and ignored multi-directional impacts and all other Rugby Union match related contact between players that did not constitute a tackle. The present study considered a players total tackle count as the total number of times that the player was involved in a tackle that halted the progress of an opponent in possession of the ball regardless of the direction of the collision. The classification of a tackle versus a hit-up in the present study is representative of a "tackle" as defined by Takarada (426). Our findings also support the results of Smart et al., (401) who reported significant correlations between game time, time defending and hit-ups and plasma [CK] in forwards and backs during Rugby Union match-play. In an analysis of immunoendocrine markers following an international level Rugby match, Cunniffe et al., (110) reported significant correlations between serum CK activity and player involvement in tackles and match-related contact events and support the findings of the present study.

The relationship between plasma [CK] and the impact characteristics of collisions during Rugby elite League match-play using integrated accelerometer technology within portable GPS has not been investigated previously. Variation in mean total tackles and hit-ups (Table 26) in comparison to the total number of Zone 4, 5 and 6 entries (Table 27) during match-play was found in the present study. The disparity in the total number of tackles and hit-ups compared to the number of impact zone entries is likely to be due to impact experienced by players during missed tackles, incomplete tackles, line breaks during hit-ups, second effort during tackles and or hit-ups and "off the ball" collisions between players that were not included in the present study. Our findings with respect to the number of Zone 4, 5 and 6 entries and plasma [CK] post-match indicated that skeletal muscle damage during Rugby League match-play is dependent upon the number and intensity of collisions experienced by players.

To our knowledge, no studies have examined plasma CK activity in response to elite Rugby League match-play or during the post-match recovery period. Furthermore, while plasma [CK] remained elevated for at least 120 hr post-match in the present study, a gradual reduction in mean plasma [CK] was identified during the short term post-match recovery phase that coincided with reduced post-match training loads and physical trauma. Similar reductions in plasma CK activity have been observed in studies that have examined endocrine and biochemical responses to tapering in team sport

athletes (97, 209). The most likely cause for the reduction in plasma [CK] during the post-match recovery period in the present study is the removal of repeated blunt force trauma that is characteristic of elite Rugby League training and match-play, a general reduction in the volume and intensity of training loads and a corresponding reduction in eccentric muscle contractions during training. On the basis of the time course associated with the response of plasma [CK] to the demands of match-play during the persent study, we suggest that the analysis of plasma [CK] can be incorporated into post-match player assessment methodologies to monitor recovery following elite Rugby League match-play.

7.5 Practical Applications

The present study provides an insight into the relationship between the pre-match and short term post-match biochemical and endocrine responses to the intensity, number and distribution of impacts associated with collisions during elite Rugby League match-play using contemporary GPS and integrated accelerometer performance analysis methodologies that have not been reported previously. The findings of the present study suggest that repeated high intensity collisions during elite Rugby League match-play are associated with significant skeletal muscle damage with plasma [CK] peaking 24 hr post-match. Elite Rugby League players can also expect to sustain blunt force trauma and impact > 7 G due to high intensity collision approximately every 50 s during match-play. The number of heavy to severe impacts experienced by players during match-play is correlated with significantly increased plasma [CK] for at least 72 hr post-match. Significantly increased plasma [CK] found immediately post-match that remanined elevated for at least 120 hr post-match suggests that training volume and intensity should be carefully monitored for at least 5 days post-match to optimise recovery from skeletal muscle damage sustained during elite Rugby League match-play.

The endocrine profile depicted in the present study found no correlation between [sCort] and impacts experienced by players during elite Rugby League match-play. A significant acute increase in [sCort] in response to match-play was identified however, followed by a return to sCort homeostasis within 48 hr, demonstrating the value of [sCort] as a viable post-match analysis measure. The time-course associated with a return of [sCort] to pre-match levels following elite Rugby League match-play supports the recommended implementation of a minimum of two days of modified activity to facilitate the short-term post-match recovery phase. When integrated with GPS and integrated accelerometer technologies, biochemical and endocrine measures can assist coaches and sports scientists to determine the demands of Rugby League competition and establish a comprehensive profile of individual plasma [CK] and [sCort] responses to elite Rugby League match-play.

Chapter 8

General Discussion, Conclusions and Future Research

8.1 The Role of Rate of Force Development on Vertical Jump Performance.

Muscle strength, power and the PRFD are considered key determinants of neuromuscular function and performance in sporting events that require high force generation in an explosive manner (106) and sports characterised by intermittent bouts of high-intensity activity (22), such as elite Rugby League match-play. Traditionally, isometric dynamometry has been a popular method for assessing neuromuscular function in athletes. However, the evolution of portable force-plates and an emphasis shift in professional sports to the inclusion of testing protocols that either directly represent or share characteristics of specific sports performance and the incorporation of SJ and CMJ assessement methodologies for functional testing and monitoring purposes has become commonplace in professional sports. Peak force, PRFD and PP have been established as important variables associated with VJ and sports performance and also to distiguish levels of athletic ability (260, 416) and tests involving the SSC, such as the CMJ, have been found to be valid and reliable tests for determining lower limb force and power (295).

During CMJ performance, the considerable requirement of force and power performance is apparent and during sporting competition, the ability to produce maximum force in the shortest time possible is key to optimal performance. The PRFD has important functional significance in rapid and forceful muscle contractions in activities such as running, jumping and sprinting that are associated with short muscle contraction times that may not allow maximal force to be achieved. As a result, the PRFD becomes an important measure of sports performance. The correlation between PRFD and VJ performance has recently been established (238) while other researchers (364, 468) have reported dynamic tests of PRFD, such as the CMJ, to be superior to isometric PRFD tests to assess dynamic muscular function and performance.

The results of the present research further indicate that maximal unloaded VJD, measured via CMJ on a force plate, is primarily determined by PRFD. Of the force time variables measured during the CMJ movements in the present research, 46.4 % of VJD was determined by PRFD and as such was the largest contributor to VJD with a significant correlation ($r = 0.68$; $p < 0.01$) between VJD and PRFD during the CMJ movement in young physically active men. The findings of the present research

accept the hypothesis that there will be a significant correlation between PRFD and CMJ performance and indicate that individuals who produce greater PRFD will produce superior VJ performance. Furthermore, the significant ($p < 0.01$) correlation between PRFD and VJD suggests that CMJ performance using the jump and reach method is primarily due to the ability to develop force rapidly and to a lesser extent maximal strength or PF. Accordingly, training methods emphasising explosive movement technique that are designed to improve PRFD should lead to improvements in VJ and ultimately improved dynamic sports performance.

In addition to PRFD, PF was significantly correlated ($r = 0.51$; $p = 0.023$) with VJD and was found to contribute 26 % to VJD during the CMJ suggesting that the maximum muscular strength of an individual also contributed to VJD. The influence of PF on VJD during the CMJ suggests that maximal strength training designed to develop PF should be included in strength training programs to improve VJ and sports performance. The present research found high test-retest reliability (CV range: 2.8 – 5.1 %) and high test-retest correlations (ICC range: 0.91 - 0.99) for PF, PP and AP during both the CMJ and SJ tests and confirm the use of these force-time variables as appropriate test parameters during VJ assessment in athletes participating in exercise involving the SSC, such as elite Rugby League players. While PRFD, TPF and ARFD for the CMJ and SJ demonstrated low test-retest reliability (CV range: 11.8 - 17.9 %) and test-retest correlations (ICC rang: 0.72 - 0.97), the present research included individuals that were inexperienced in dynamic explosive exercise and as such the results were in contrast to others (238) using experienced strength-power athletes that were well accustomed to explosive exercise. These results of the present research highlight the influence of training status as a key determinant of an individual's ability to rapidly harness PF and achieve the fastest TPF, which as determined in the present research is significantly ($p < 0.05$) related to PRFD.

Although the results of the present research suggest that caution should be taken with the use of PRFD data to determine VJ performance in untrained individuals, training status remains a key determinant of an athlete's ability to achieve rapid TPF and concomitant PRFD. The findings of the present research confirm the inclusion of PF and PP as reliable measures of SJ and CMJ analysis and support inclusion of explosive type training with minimal loading to improve PRFD and traditional heavy strength training to enhance PF in individuals to improve VJ performance. Furthermore, these results support the regular inclusion of force-time measures PF, PP and PRFD for athlete testing and monitoring purposes in the field.

8.2 Performance Analysis of Elite Rugby League Match-Play using Global Positioning Systems.

Despite the popularity of Rugby League in Australia, and the professional status of players in the NRL, there remains a lack of information about the physiological demands and movement patterns of elite players during match-play. Recent studies have added to our understanding of the physiological demands of Rugby League however as more advanced technologies for performance analysis emerge there is a need for a concomitant increase in evaluation and analysis of that information to improve training practices and performance outcomes. Accordingly, analysis of NRL match-play incorporating portable GPS and integrated accelerometer technology has become commonplace with professional teams. However, no study has examined the physiological requirements or movement characteristics of Rugby League match-play using GPS and integrated accelerometer technology. The present research therefore provides an insight to elite Rugby League match-play not considered previously and constitutes novel research that adds to our understanding of the performance requirements of elite Rugby League match-play.

The results of the current research indicate that elite Rugby League players are required to complete frequent bouts of high-intensity activity separated by short bouts of low-intensity activity. While the present research found no significant positional differences in the total distances covered between backs and forwards during match-play, considerable differences were identified between the physiological and movement demands of forwards and backs in the frequency, duration and distances associated with high-intensity running activity. Simultaneous measurement of HR and movement patterns during match-play using real-time GPS and integrated accelerometer technology also revealed positional variation in the physiological requirements of competition. Interestingly, exercise-to-rest ratios determined from distance covered in each speed zone during match-play were 1:6 and 1:7 for backs and forwards respectively and allow the hypothesis to be accepted that there will be substantial positional differences in movement patterns and exercise-to-rest ratio activities during elite Rugby League match-play. Although exercise-to-rest ratios provide important information on match-play demands, data calculated from player running distances may however underestimate actual exercise time during Rugby League match-play and as such this data should be viewed with caution. Exercise-to-rest ratios in the present research were determined in accordance with traditional methodologies that do not consider the substantial time spent participating in Rugby League match-play specific pushing, pulling and wrestling activities that register as low-intensity activity using GPS and integratd accelerometer technology despite the highly intensive nature of the exercise in a stationary position.

Nevertheless, the exercise-to-rest ratios in the present research indicate that most of the energy required to perform the periods of high-intensity activity is derived from the ATP-PC system and anaerobic glycolysis. Accordingly, the aerobic capacity for elite rugby league players should be high, as the average HR of players equating to > 70 % of HR_{max} for the duration of match-play, and particularly so for forwards who spend > 50 % of match-play performing activities at > 85 % HR_{max}. These results of the present research allow the hypothesis to be accepted that portable GPS and integrated accelerometry and HR monitoring will provide a detailed and specific analysis of player movement patterns, high intensity and low intensity match-play activities and the HR response to the demands of elite Rugby League match-play. Furthermore, the current research supports the traditionally held view that there is a large aerobic component required for the performance of elite Rugby League match-play. The present research confirmed that a large component of match-play is spent performing non-locomotor high-intensity activities such as pulling, pushing and tackling, therefore a combination of GPS-integrated accelerometer technology and video recordings of match-play may provide greater insight into the determination and categorisation of impact forces and or accelerations and decelerations sustained or exerted during the frequent and varied contact components of elite Rugby League match-play.

The contribution of the present research to the understanding of the physiological and movement characteristics of elite Rugby League match-play are evident on the basis that the use of GPS-integrated accelerometer technology as a mode of match-play analysis was approved by the NRL in February 2009. Data presented in the present research therefore has a high degree of novelty and provides an up to date analysis of NRL match-play under current rules and regulations. The present data supersede the recent but now outdated work of others (246, 396) that have reported data from 2004 and 2005 NRL seasons under pre-existing interchange rules, referee involvement and rule structures. Furthermore, the increased understanding of the demands of elite Rugby League match-play that is provided by the present research is required to improve awareness of individual performance characteristics and implement a systematic approach to the development of position specific training programs and recovery protocols to optimise performance.

8.3 Creatine Kinase and Endocrine Responses of Elite Players Pre, During, and Post Rugby League Match-Play.

The combative nature of elite Rugby League match-play is characterised by repeated high velocity blunt force trauma and physical collisions that are typically experienced by players in Rugby Union and American Football. Frequent physical collisions during match-play are intersperesed with running

volumes and sprint profiles during elite Rugby League match-play that are comparable with soccer and Australian Rules Football and provide a unique model to examine the time-course of biochemical and endocrine responses to elite Rugby League match-play using GPS and accelerometer technology that have not been reported previously. The findings of the present research indicate that the demands of elite Rugby League match-play result in significant skeletal muscle damage immediately post-match ($p < 0.05$; ± 56 %) and is reflected by peak plasma [CK] measured 24 hr ($p < 0.05$; ± 91 %) post-match. Although eccentric muscular work has traditionally been considered the predominant contributor to increased plasma [CK] after exercise (57), the present findings are consistent with recent evidence (401) suggesting physical collisions and blunt trauma may contribute to inceased plasma [CK] post-contact sport participation.

Although no significant positional difference was evident between plasma [CK] and total distances travelled during match-play, the backs covered greater distance at high-intensity running (135 ± 49 m; $p = 0.03$) and sprinting speeds (290 ± 69 m; $p < 0.01$) compared to the forwards (82 ± 21 m & 149 ± 32 m respectively). The repeated high intensity acceleration and deceleration associated with sprinting bouts performed by backs, requires considerable eccentric hamstring muscle activity. An increased likelihood of structural damage associated with eccentric muscle activity may contribute to the plasma CK response of backs to elite Rugby League match-play. Alternatively, the exposure of forwards to repetitive high intensity collisions during match-play may contribute to acute soft tissue trauma and structural damage to muscle tissue. Elevated plasma [CK] in the present research persisted in comparison to pre-match levels despite 120 hr of modified activity post-match, suggesting that training volume and intensity should be closely monitored and reduced during the short term recovery period for at least five days to optimise recovery of muscle damage sustained during match-play and to optimise subsequent performance.

The endocrine responses to elite Rugby League match-play are unreported. Therefore, the analysis of sTest and sCort was included in the present research to incorporate a relatively simple, non-invasive measure of endocrine changes before, during and after Rugby League match-play. The sT:C was included to examine the anabolic:catabolic endocrine profile of players following competition and during the short-term recovery phase post-match. Although no significant correlation was found for sTest or sCort and the total distance travelled, the endocrine profile of players in the present research identified a significant and acute increase ($p < 0.05$) in sCort and a significant decrease in sTest ($p < 0.05$) in response to elite Rugby League match-play followed by a return to hormonal homeostasis within 48 hr. Accordingly, a significant ($p < 0.05$) decrease in sT:C ratio was identified immediately after the match that remained reduced in comparison to pre-match baseline levels for 48 hr post-match. The findings of the present research are the first to report the sTest, sCort and sT:C response to elite Rugby League match-play. Although considerable variation exists between the performance

characteristics of other contact sports, such as Rugby Union and Australian Rules Football and those of elite Rugby League, the findings of the present research consistent with the results of others (86, 137) that have examined the acute endocrine response to contact sport particiaption.

The influence of individual biological responses, specialised team recovery protocols including nutrition and hydration regimes, travel commitments and weekly team training schedules all contribute to a players' ability to recover from match-play in an optimal time frame. The use of the sT:C ratio to represent the anabolic:catabolic endocrine profile of athletes following competition has implications for the design and implementation of training programs during the course of a competitive season. The ability to monitor the anabolic:catabolic endocrine profile of elite players is particularly important in a heavy contact team sport environment that is undertaken throughout the course of a prolonged regular season period, such as that experienced by players during 24 matches in 26 weeks in the NRL. The return of the post-match sT:C ratio to baseline within 48 hr as identified in the present study is indicative of a successful recovery of [sTest] and [sCort] and thereby suggests a restoration of resting anabolic:catabolic hormone profile in elite Rugby League players. A recovery protocol consisting of closely monitored, modified activity for a minimum of 48 hr is therefore recommended to enable anabolic:catabolic endocrine homeostasis to be achieved post- elite Rugby League match-play.

The results of the present study allow the hypothesis to be accepted that Rugby League match-play will result in significant skeletal muscle damage and significant elevation in sCort levels post-match. Moreover, the present research provides an insight to player movement patterns during elite Rugby League match play using contemporary GPS-integrated accelerometer performance analysis methods that have not been reported previously. The evolution of real-time data acquisition with respect to player movement characteristics in team sports will continue to facilitate a more robust analysis approach and enable sports scientists and coaches to further quantify the requirements of performance. By comparing the biochemical and endocrine responses to competition, coaches and sports scientists are able to establish individual responses and adaptation to elite Rugby League match-play.

8.4 Markers of Post-Match Fatigue in Professional Rugby League Players.

Participation in contact sport such as Rugby League that involves high intensity, intermittent exercise and blunt force trauma is a complex phenomenon, often associated with significant neuromuscular fatigue. Although the CMJ is commonly used to assess SSC activity and athletic performance, there are limited data that have used the CMJ to determine the effect of competitive match-play on neuromuscular fatigue (11, 86), and the neuromuscular response of elite Rugby League players to competition. Accordingly, the ability to quantify decrements in key performance indicators such as

lower body force and power characteristics and establish the neuromuscular status of elite Rugby League players post-match via an easy to administer functional test such as the CMJ and SJ may enable coaches and sports scientists to make informed decisions regarding recovery protocols and subsequent training programs and schedules.

Incorporating the primary determinants of CMJ performance established in experimental study one, changes in the force-power characteristics of players following elite Rugby League match-play revealed that PRFD was significantly lower 30 min post-match ($p = 0.026$) and 24 hr post-match ($p = 0.042$) compared to 30 min pre-match. The PRFD remained below pre-match values for 48 hr post-match, and may reflect the influence of impaired excitation-contraction coupling reported with LFF on decreased PRFD, PP and PF 24 hr following Rugby League match-play. Acute reductions in PRFD following team sport competition are consistent with the results of some (438) but not other researchers (216) and further highlights the degree of caution that must be taken when making comparisons between the neuromuscular and physiological requirements of Rugby League and other field based team sports such as American Football and Soccer.

The PP in the present research was significantly lower 30 min post-match ($p = 0.005$) and 24 hr post-match ($p = 0.034$) compared to 30 min pre-match values. It would appear that both the velocity of the CMJ, evidenced by the reduction in PRFD, and the force as evidenced by the reduction in PF 30 min post-match, may have contributed to the decrease in PP. The decrease in PP remained until 48 hr post-match suggesting that the velocity component of PP was more sensitive to fatigue than the force component. Following 30 min recovery post-match, PF decreased significantly ($p = 0.031$), followed by a return to pre-match values within 24 hr post-match, allowing the hypothesis to be accepted that Rugby League match-play will result in significantly reduced neuromuscular performance during the CMJ post-match. The cause of the decrease in PF observed 30 min post-match may be due to a combination of central fatigue in the form of reduced central drive, and peripheral fatigue in the form of an impairment in action potential propagation over the sarcolemma (HFF) or impaired excitation-contraction coupling (LFF). The present results are consistent with other researchers (62) and suggest that PF (also referred to as maximal strength) recovers more quickly than PP or PRFD following elite Rugby League match-play. It would appear that both the velocity of the CMJ, evidenced by the reduction in PRFD and the force, as evidenced by the reduction in PF 30 min post-match, may have contributed to the decrease in PP. The decrease in PP remained until 48 hr post-match suggesting that the velocity component of PP was more sensitive to fatigue than the force component and as such, PP and PRFD may be more useful than PF in monitoring neuromuscular fatigue following elite Rugby League match-play. Accordingly, the results of the present research allow the hypothesis to be accepted that PF, PP and PRFD are useful measures to assess neuromuscular fatigue in elite Rugby League players and to monitor recovery following NRL match-play.

The findings of the present research indicate skeletal muscle damage occurs as a result of the demands of elite Rugby League match-play, and is reflected by peak plasma [CK] (941 ± 392 $U \cdot L^{-1}$) measured 24 hr ($p < 0.05$) post-match. As established in experimental study three, elevated plasma [CK] persisted in comparison to pre-match ($p < 0.05$) levels despite 120 hr of modified activity post-match suggesting a training volumes and intensity should be closely monitored for at least five days to ensure full recovery of muscle damage following elite Rugby League match-play. Although the effect of elevated plasma [CK] upon athletic performance is unclear, the present research found a significant correlation between the increase in plasma [CK] and decreased PRFD 30 min post-match ($p = 0.044$, $r = -0.65$) and 24 hr post-match ($p = 0.033$, $r = -0.58$). The results of the present research suggest that the decrease in PRFD 30 min post-match and 24 hr post-match is causally related to the increase in plasma [CK]. These findings are consistent with the results of others (11, 326) that have reported similar relationships between CMJ performance and [CK] following soccer match play and exhaustive SSC exercise respectively. The associated increase in plasma [CK] with decreased PRFD suggests that a CMJ may be used as an indirect estimate of the exercise-induced muscle damage (EIMD) from Rugby League match-play. Support for a CMJ as an indirect estimate of PRFD is based on the reported relationship between [CK] and decreased SSC performance (250). The present findings indicate that the use of the CMJ as a functional indicator of PRFD, PP, PF and EIMD may therefore provide an appropriate method of functional impairment analysis associated with skeletal muscle damage and recovery times following Rugby League match-play.

The [sCort] profile depicted in the present research identified a substantial acute [sCort] increase ($p < 0.05$) in response to elite Rugby League match-play followed by a return to endocrine homeostasis within 48 hr. Similar post-match cortisol levels have been reported following competition in other football codes (86, 137), and suggest a minimum period of 48 hr of modified activity post-match is required to enable [sCort] to return to pre-match rested levels. The present research also found a significant correlation between change in [sCort] and the decrease in PF 30 min post-match ($p = 0.048$, $r = -0.58$). No other study has examined the relation between [sCort] and PRFD, PP and PF following Rugby League match-play. Although the relationship between decreased PF and increased [sCort] is unclear, the results of the present research indicate that those players with the largest decrement in PF also produced the highest [sCort] 30 min post-match. Decreased PF may reflect neuromuscular fatigue via an elite Rugby League match-play induced decline in central drive and failure of the excitation contraction mechanism (2) in players who experienced greater psychological stress or completed more high intensity activity for longer duration, resulting in higher post-match [sCort].

The findings of the present study indicate that the PRFD measured during a CMJ may be used as a mechanism to determine the neuromuscular fatigue associated with competitive Rugby League match-

play. Elevated plasma [CK] for up to 120 hr post-match suggests significant damage to muscle tissue as a result of the blunt force trauma associated with high speed collisions among elite Rugby League players. Peak RFD, PP and PF returned to pre-match levels within 48 hr post-match, indicating an absence of neuromuscular fatigue and a preparedness of players to undertake strength training despite a prolonged presence of muscle damage as indicated by elevated plasma [CK]. Accordingly, the neuromuscular and biochemical markers incorporated into experimental studies three and four of the present thesis show promise as predictors of neuromuscular fatigue, recovery and readiness for subsequent training following elite Rugby League match-play. Furthermore, analysis of neuromuscular, biochemical and endocrine markers pre- and post-match and may enable coaches and sports scientists to establish a comprehensive profile of individual responses and adaptation to elite Rugby League match-play and modify training programs on an individual basis to optimise performance.

8.5 Biochemical and Endocrine Responses to Impact and Collision During Elite Rugby League Match-Play.

The use of data obtained from portable GPS-integrated accelerometer units to determine the level of impact associated with player collisons during elite Rugby League match-play combined with the examination of biochemical and endocrine responses to match-play as outlined in experimental chapters three and four represents a novel approach to investigating the physical demands of competition and the short term recovery phase response in the NRL. The evolution of real-time data acquisition of impacts experienced by players during match-play collisions presents sports scientists and coaches with increased scope to quantify the sport specific requirements of elite Rugby League competition. Furthermore, the investigation of biochemical and endocrine responses of players to the incidence and degree of impact during match-play collisions represents a considerable increase in performance analysis methodology in elite Rugby League. Accordingly, it is likely that the incorporation of post-match biochemical and endocrine monitoring practices will enable sports scientists to identify individual responses to competition, facilitate the post-match recovery process and optimise subsequent performance.

The present findings indicate that the demands of repeated high intensity collisions during elite Rugby League match-play are associated with significant skeletal muscle damage, indicated by an increased plasma [CK] 30 min post-match ($p = 0.003$). The increase in plasma [CK] 30 min post-match is consistent with the results of others (401, 426) and indicates an acute plasma [CK] response to trauma associated with high speed collisions between and among players and the playing surface during

match-play. Peak plasma [CK] (979 ± 415 $U \cdot L^{-1}$ and 922 ± 380 $U \cdot L^{-1}$ for forwards and backs respectively) was identified 24 hr ($p = 0.002$) post-match and are consistent with the results of others (215, 259) that have incorporated CK assessment to investigate the degree of skeletal muscle damage during contact sports. The present study is the first to examine the plasma CK response to collisions during elite Rugby League match-play. The findings of the present research support the implementation of prolonged plasma [CK] analysis for a minimum of 18 - 96 hr post competition (80, 426) to determine peak plasma [CK] post-match and monitor the time-course of a return to pre-match plasma [CK] following elite Rugby League match-play.

Body impacts experienced by players during high intensity collisions between opposing players and the playing surface are associated with impact forces > 7.1 G. Significant correlation ($p < 0.05$) between the number of impact collisions > 7.1 G and plasma [CK] were identified 30 min post-match and 24 hr post-match. Furthermore, a significant correlation ($p < 0.05$) was found between the number of impact collisions > 8.1 G and plasma [CK] 48 hr and 72 hr post-match. The results of the present research indicate that regardless of the nature of contact, exposure to high impact collisions > 7.1G caused significant skeletal muscle damage during match-play that peaked 24 hr post-match. The correlation between high intensity collisions and plasma [CK] have not been reported previously and are likely to reflect greater skeletal muscle damage associated with heavy blunt force trauma and repeated high intensity collisions during elite Rugby League match-play.

The present research found no significant positional difference between the total number of collision related impacts for forwards and backs during offensive and defensive match-play. To differentiate the physical consequences of offensive versus defensive match-play, the present study investigated the relationship between the number of tackles, the number of 'hit-ups' and plasma [CK] within 30 min post-match and at 24 hr intervals for a period of 120 hr post-match. The present research found that elite Rugby League players can expect to sustain blunt force trauma and impact due to high intensity collision with an opponent or the playing surface approximately every 50 s during match-play. Although the present research found no significant correlation between the number of tackles a player performed and plasma [CK] immediately post-match, or during the 120 hr post-match recovery period, a significant ($p < 0.05$) correlation was found between the number of hit-ups performed by players and plasma [CK] for up to 3 days post-match. Overall, the plasma [CK] remained significantly elevated ($p < 0.05$) for at least 120 hr post-match, therefore a recovery phase of at least five days of carefully monitored training volume and intensity is recommended to achieve complete recovery of skeletal muscle damage sustained during elite Rugby League match-play.

The endocrine profile depicted in the present research identified that a significant acute [sCort] response to elite Rugby League competition followed by a rapid return to homeostasis within 48 hr is

independent to the number of collisions a player experiences during match-play. Consequently, the results of the present research allow the hypothesis to be accepted that blunt force trauma associated with impacts that are characteristic of elite Rugby League match-play will result in significant skeletal muscle damage and significantly increased stress hormone levels post-match. Although salivary endocrine measures may provide an easy to administer, non-invasive mode of assessing a players endocrine response to competition, the absence of any correlation between [sCort] and impacts experienced by players during match-play may limit the usefulness of this measure to monitor the effects of blunt trauma and repeated physical collisions on performance and recovery. The present findings indicate that plasma [CK] provides a more appropriate method of monitoring the demands of competition and the time-course associated with recovery following elite Rugby League match-play.

Collectively, the applied implications of the experimental studies presented in this body of research indicate that the magnitude and frequency of repeated blunt force trauma during elite Rugby League match-play results in considerable skeletal muscle damage and a concomitant endocrine stress response. The underlying practical application of elevated biochemical and endocrine markers post NRL match-play has been associated with a decrement in functional performance measures and the presence of neuromuscular fatigue post-match. When integrated with neuromuscular, biochemical and endocrine measures, information regarding the physiological demands of elite Rugby League match-play may be incorporated into individual player monitoring and profile development, and can assist with determining training demands, recovery procedures, injury prevention protocols, rehabilitation and return to play strategies.

8.6 Recommendations for Future Research.

The present research provides insight into the acute and short-term post-match recovery period neuromuscular, biochemical and endocrine markers of fatigue, muscle damage and physiological stress following elite Rugby League match-play. To further increase our understanding of the demands of elite Rugby League match-play, recovery and preparation for subsequent performance the following directions for research may build upon the results of the present research.

1. To increase our understanding of the evolution of elite Rugby League match-play, a more comprehensive analysis of match-play across all NRL teams would benefit coaches and sports scientists to further define the requirements of position specific performance and improve athlete preparation and recovery methodologies.

2. The incidence of repeated high-velocity blunt trauma and physical collisions during elite Rugby League match-play has a substantial influence on a players' performance and recovery. Investigation of the relationship between the incidence of high-intensity collision, muscle damage and markers of neuromuscular fatigue may be of interest and provide a more comprehensive analysis of elite Rugby League match-play.

3. To complement the present research, examination of additional markers of inflammation (e.g. Cytokines and interleukins) and immuno-suppression (eg. Immunoglobulins) and subjective measures of pain in response to single match, multi-match and season long periods of match-play would provide novel research not considered previously in elite Rugby League players.

4. The present research has provided novel research regarding the neuromuscular biochemical, endocrine and physiological responses of elite players to Rugby League match-play. To build upon this research, analysis of neuromuscular patterns of fatigue, skeletal muscle damage and endocrine responses to a full season of match-play would be beneficial.

5. Subsequent to the completion of the present research, further advances in match analysis technologies may now enable investigators to accurately quantify offensive and defensive impact profiles associated with collisions in contact sports. Research to differentiate the neuromuscular, biochemical, endocrine and physiological responses to collision as an offensive or defensive player would be of interest to coaching and performance staff in elite contact sport.

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